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Combined and Co-ordinated Sciences

for Cambridge IGCSE™

COURSEBOOK

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Introduction

This book covers two syllabuses: Cambridge IGCSE Combined Science (0653) and the double award Cambridge IGCSE and IGCSE (9-1) Co-ordinated Sciences (0654/0973). We hope that you enjoy using it.

All the biology topics come first, followed by chemistry and then physics. However, you almost certainly won't follow this sequence in your lessons. Where possible, the book follows the order of topics in the syllabus. Some topics have been merged or moved where concepts are closely related. You will probably find that you study biology, chemistry and physics alongside each other, so you will use different parts of the book in different lessons.

Core and Supplement

Your teacher will tell you whether you are studying:

- Cambridge IGCSE Combined Science 0653 or Cambridge IGCSE and IGCSE (9-1) Co-ordinated Sciences (Double Award) 0654/0973
- only the Core part of the syllabus, or the Supplement as well.

Cambridge IGCSE Combined Science 0653 is a single award syllabus. This means that your final papers are the equivalent of one IGCSE subject. Cambridge IGCSE and IGCSE (9-1) Co-ordinated Sciences 0654/0973 is a double award syllabus. In this case, your final papers are the equivalent of two IGCSE subjects.

If you study 0654 Core only, you will be entered for Papers 1 (Multiple Choice (Core)) and 3 (Theory (Core)) and either Paper 5 (Practical Test) or 6 (Alternative to Practical). If you also study the Supplement, you may be entered for Papers 2 (Multiple Choice (Extended)) and 4 (Theory (Extended)), and either Paper 5 (Practical Test) or 6 (Alternative to Practical).

There are sidebars in the margins of the coursebook to show which material relates to each syllabus and paper. If there is no sidebar, it means that everyone will study this material.

Use this table to ensure that you study the right material for your syllabus and paper:

Cambridge IGCSE Combined Science (0653)		Cambridge IGCSE Co-ordinated Sciences (0654)	
Core	Supplement	Core	Supplement
You will study the material:	*You will study the material:*	*You will study the material:*	*You will study everything which includes the material:*
Without a sidebar	Without a sidebar	Without a sidebar	Without a sidebar
	With a dashed blue sidebar	With a solid blue sidebar	With a dashed blue sidebar
	With a dashed black sidebar	With a dashed black sidebar	With a dashed black sidebar
	You will not study material with a solid blue sidebar or a solid black sidebar.	*You will not study material with a solid black sidebar or a dashed blue sidebar.*	With a solid blue sidebar
			With a solid black sidebar

A simplified table has also been included on the inside back flap of this coursebook to open out and view alongside the exercises.

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Questions

Each chapter has several sets of questions within it. Most of these require quite short answers and simply test if you have understood what you have just read or what you have just been taught.

At the end of each chapter, there are some longer questions testing a range of material from the chapter. Some of these are written by the authors and are similar in style to Cambridge questions.

Activities

Just learning your work and remembering it is not enough to make sure that you achieve your best result in your exam. You also need to be able to use what you've learned in unfamiliar contexts (AO2) and to demonstrate your experimental skills (AO3).

Each chapter contains activities. These will help you to develop the practical skills you will need in your course.

There are two possible papers aimed at testing your practical skills, Practical Test and Alternative to Practical, respectively. Your teacher will tell you which of these you will be entered for. You should try to do the activities in this coursebook no matter which of these papers you are entered for.

Summary

At the end of each chapter, there is a short list of the main points covered in the chapter. Remember, though, that these are only very short summaries and you will need to know more detail than this for your course.

Projects

You will find a project at the end of every chapter, which gives you the opportunity to work in groups, exercise your creativity, and develop your research and critical thinking skills.

Workbooks

There are three workbooks to go with this coursebook – one for each science. If you have the workbooks, you will find them really helpful in developing your skills, such as handling information and solving problems, as well as some of the practical skills.

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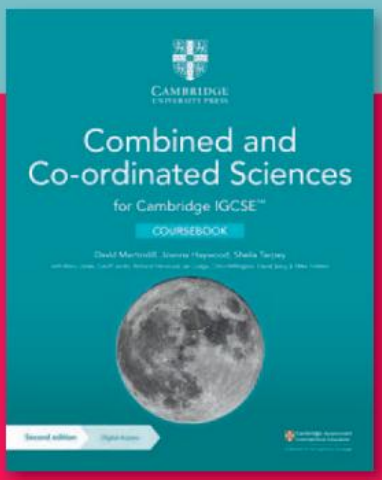
How to use this series

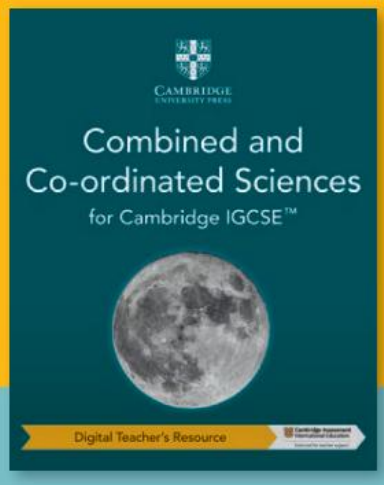
We offer a comprehensive, flexible array of resources for the Cambridge IGCSE™ Combined Science syllabus (0653) and Cambridge IGCSE and IGCSE (9-1) Co-ordinated Sciences syllabuses (0654/0973) for examination from 2025. We provide targeted support and practice for the specific challenges we've heard that students face: learning science with English as a second language; structured learning for all; and developing practical skills.



The coursebook provides full coverage of the Cambridge IGCSE syllabuses 0653 and 0654/0973. Each chapter explains facts and concepts, and uses relevant real-world examples of scientific principles to bring the subject to life. Together with a focus on practical work and plenty of active learning opportunities, the coursebook prepares learners for all aspects of their scientific study. Questions and practice questions in every chapter help learners to consolidate their understanding and provide practice opportunities to apply their learning.

The teacher's resource contains detailed guidance for all topics of the syllabuses, including common misconceptions identifying areas where learners might need extra support, as well as an engaging bank of lesson ideas for each syllabus topic. Differentiation is emphasised with advice for identification of different learner needs and suggestions of appropriate interventions to support and stretch learners. The teacher's resource also contains support for preparing and carrying out all the investigations, including a set of sample results for when practicals aren't possible.

The teacher's resource also contains scaffolded worksheets and unit tests for each chapter. Answers for all components are accessible to teachers for free on the Cambridge GO platform.



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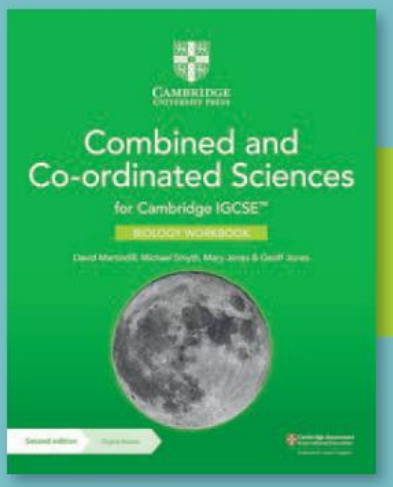
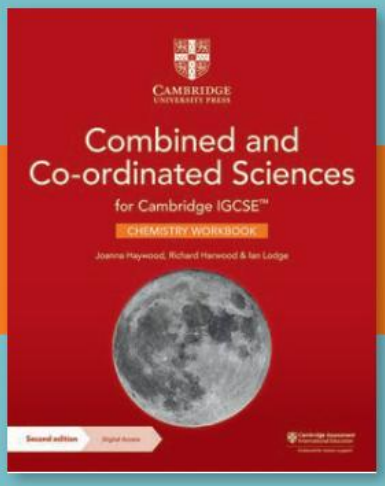
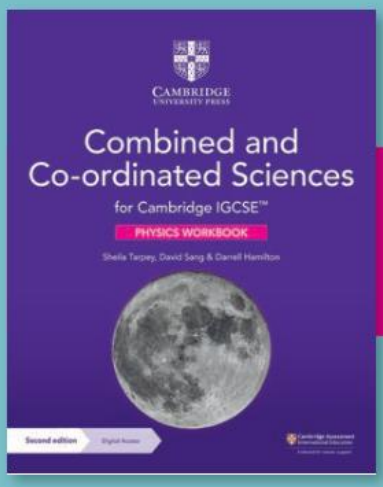
The skills-focused workbooks have been carefully constructed to help learners develop the skills that they need as they progress through their Cambridge IGCSE™ Combined and Co-ordinated Sciences course, providing further practice of some of the topics in the coursebook, each science with its own separate workbook. A three-tier, scaffolded approach to skills development enables students to gradually progress through 'focus', 'practice' and 'challenge' exercises, ensuring that every learner is supported. The workbooks enable independent learning and are ideal for use in class or as homework.







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How to use this book

Throughout this book, you will notice lots of different features that will help your learning. These are explained below.

LEARNING INTENTIONS

These set the scene for each chapter, help with navigation through the coursebook and indicate the important concepts in each topic. They will begin with the header 'In this chapter you will:' and will list the key topics of the chapter for all students.

IN THIS CHAPTER YOU WILL:

- learn about the seven characteristics of living organisms
- find out how the binomial system is used to name organisms

BEFORE YOU START

This contains questions and activities on subject knowledge you will need before starting this chapter.

EXPERIMENTAL SKILLS

This feature focuses on developing your practical skills. They include lists of equipment required and any safety issues, step-by-step instructions so you can carry out the experiment, and questions to help you think about what you have learnt.

ACTIVITY

Activities give you an opportunity to check and develop your understanding throughout the text in a more active way, for example by creating presentations, posters or role plays. Where activities have answers, teachers can find these for free on the Cambridge GO site.

SELF/PEER ASSESSMENT

At the end of some activities and experimental skills boxes, you will find opportunities to help you assess your own work, or that of your classmates, and consider how you can improve the way you learn.

Questions

Appearing throughout the text, questions give you a chance to check that you have understood the topic you have just read about. The answers to these questions are accessible to teachers for free on the Cambridge GO site.

KEY WORDS

Key vocabulary is highlighted in the text when it is first introduced, and definitions are given in boxes near the vocabulary. You will also find definitions of these words in the Glossary at the back of this book.

COMMAND WORDS

Command words that appear in the syllabus and might be used in exams are highlighted in the practice questions. In the margin, you will find the Cambridge International definition. You will also find these definitions in the Glossary at the back of the book with some further explanation on the meaning of these words.

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TIP

These contain advice to help you avoid common misconceptions and provide support for answering questions.

REFLECTION

These activities ask you to think about the approach that you take to your work, and how you might improve this in the future.

WORKED EXAMPLES

Worked examples are used to demonstrate the steps you should take to answer a specific type of question. They are followed by opportunities for you to practise the techniques for yourself.

These boxes tell you where information in the book is extension content, and is not part of the syllabus.

SUMMARY

There is a summary of key points at the end of each chapter.

PRACTICE QUESTIONS

Questions at the end of each chapter provide more demanding practice questions, some of which may require use of knowledge from previous chapters. The answers to these questions are accessible to teachers for free on the Cambridge GO site.

SELF-EVALUATION CHECKLIST

The summary checklists are followed by 'I can' statements which relate to the Learning intentions at the beginning of the chapter. You might find it helpful to rate how confident you are for each of these statements when you are revising. You should revisit any topics that you rated 'Needs more work' or 'Almost there'.

I can	See topic . . .	Needs more work	Almost there	Ready to move on

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The Periodic Table of Elements

Group																	
I	II											III	IV	V	VI	VII	VIII
							1 H hydrogen 1										2 He helium 4
3 Li lithium 7	4 Be beryllium 9											5 B boron 11	6 C carbon 12	7 N nitrogen 14	8 O oxygen 16	9 F fluorine 19	10 Ne neon 20
11 Na sodium 23	12 Mg magnesium 24											13 Al aluminium 27	14 Si silicon 28	15 P phosphorus 31	16 S sulfur 32	17 Cl chlorine 35.5	18 Ar argon 40
19 K potassium 39	20 Ca calcium 40	21 Sc scandium 45	22 Ti titanium 48	23 V vanadium 51	24 Cr chromium 52	25 Mn manganese 55	26 Fe iron 56	27 Co cobalt 59	28 Ni nickel 59	29 Cu copper 64	30 Zn zinc 65	31 Ga gallium 70	32 Ge germanium 73	33 As arsenic 75	34 Se selenium 79	35 Br bromine 80	36 Kr krypton 84
37 Rb rubidium 85	38 Sr strontium 88	39 Y yttrium 89	40 Zr zirconium 91	41 Nb niobium 93	42 Mo molybdenum 96	43 Tc technetium –	44 Ru ruthenium 101	45 Rh rhodium 103	46 Pd palladium 106	47 Ag silver 108	48 Cd cadmium 112	49 In indium 115	50 Sn tin 119	51 Sb antimony 122	52 Te tellurium 128	53 I iodine 127	54 Xe xenon 131
55 Cs caesium 133	56 Ba barium 137	57–71 lanthanoids	72 Hf hafnium 178	73 Ta tantalum 181	74 W tungsten 184	75 Re rhenium 186	76 Os osmium 190	77 Ir iridium 192	78 Pt platinum 195	79 Au gold 197	80 Hg mercury 201	81 Tl thallium 204	82 Pb lead 207	83 Bi bismuth 209	84 Po polonium –	85 At astatine –	86 Rn radon –
87 Fr francium –	88 Ra radium –	89–103 actinoids	104 Rf rutherfordium –	105 Db dubnium –	106 Sg seaborgium –	107 Bh bohrium –	108 Hs hassium –	109 Mt meitnerium –	110 Ds darmstadtium –	111 Rg roentgenium –	112 Cn copernicium –	113 Nh nihonium –	114 Fl flerovium –	115 Mc moscovium –	116 Lv livermorium –	117 Ts tennessine –	118 Og oganesson –

Key

atomic number
atomic symbol
name
relative atomic mass

lanthanoids	57 La lanthanum 139	58 Ce cerium 140	59 Pr praseodymium 141	60 Nd neodymium 144	61 Pm promethium –	62 Sm samarium 150	63 Eu europium 152	64 Gd gadolinium 157	65 Tb terbium 159	66 Dy dysprosium 163	67 Ho holmium 165	68 Er erbium 167	69 Tm thulium 169	70 Yb ytterbium 173	71 Lu lutetium 175
actinoids	89 Ac actinium –	90 Th thorium 232	91 Pa protactinium 231	92 U uranium 238	93 Np neptunium –	94 Pu plutonium –	95 Am americium –	96 Cm curium –	97 Bk berkelium –	98 Cf californium –	99 Es einsteinium –	100 Fm fermium –	101 Md mendelevium –	102 No nobelium –	103 Lr lawrencium –

The volume of one mole of any gas is 24 dm^3 at room temperature and pressure (r.t.p.).

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B1 Cells and organisms

All learners study some content in this chapter

IN THIS CHAPTER YOU WILL:

- learn about the seven characteristics of living organisms
- find out about the structure of the cells of bacteria, plants and animals
- learn about the functions of each of the cells of bacteria, plants and animals
- identify cell structures in diagrams
- describe how the structures of some specialised cells are related to their functions
- state that new cells are produced by division of existing cells
- describe the meaning of the terms cell, tissue, organ, organ system and organism
- practise using the magnification equation
- convert measurements between millimetres (mm) and micrometres (μm).

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BEFORE YOU START

Different types of organisms have different kinds of cells. With a partner, think about the answers to these questions:

1 The list below contains some features of living organisms. With a partner, discuss which of these features are found in all living organisms.

breathing **excretion** **a blood system** **a nervous system** **sensitivity**
growth **reproduction** **movement** **nutrition** **respiration**

2 If you have a microscope, how can you distinguish between a cell from a plant, and a cell from an animal?

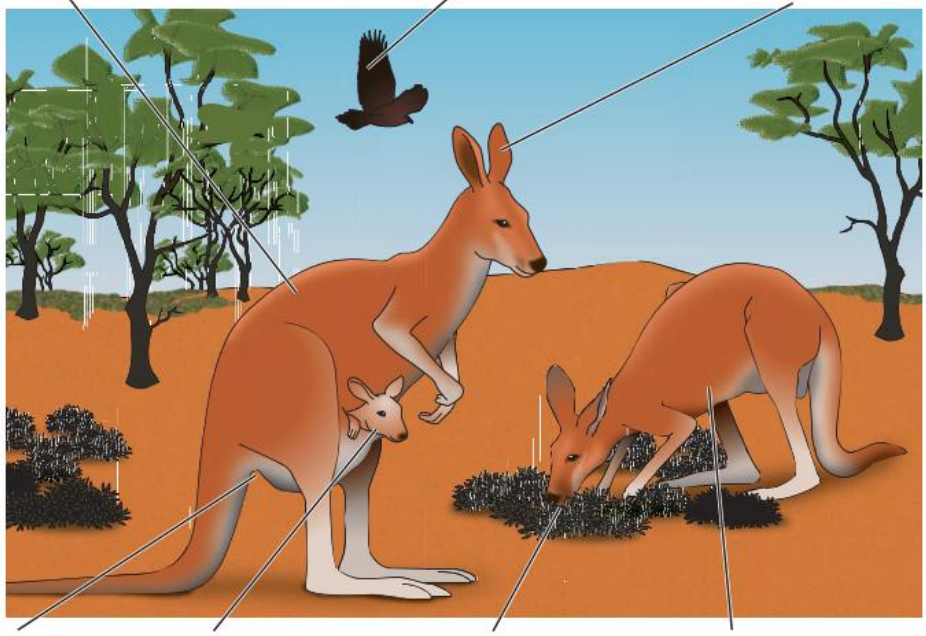
B1.01 Characteristics of living organisms

Biology is the study of organisms. An **organism** is a complete living thing – such as yourself, a platypus, a bacterium or a mango tree. There are very many different kinds of organism on Earth, but all of them share seven characteristics (Figure B1.01). Some non-living things have some of these characteristics, but no non-living thing has all of them.

Growth: All organisms begin small and get larger, by the growth of their cells and by adding new cells to their bodies. Growth can be defined as a permanent increase in size or dry mass. Measuring dry mass involves killing and drying the organism (so this method is more often used for plants than for animals). The mass of its body without any water is then found.

Movement: All organisms are able to move to some extent. Most animals can move their whole body from place to place, and plants can slowly move parts of themselves.

Sensitivity: All organisms pick up information about changes in their environment, and react to the changes. These changes may be in the internal environment (such as the temperature of the blood) or the external environment (such as the intensity of sunlight).



Excretion: All organisms produce unwanted or toxic waste products as a result of their metabolic reactions, and these must be removed from the body.

Reproduction: Organisms are able to make new organisms of the same species as themselves.

Nutrition: Organisms take substances from their environment and use them to provide energy or materials to make new cells.

Respiration: All organisms break down glucose and other substances inside their cells, to release energy that they can use. Organisms use the energy that they obtain from respiration to make other chemical reactions in their cells happen. All of these chemical reactions together – including respiration – are called metabolism.

Figure B1.01: Characteristics of living organisms.

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SCIENCE IN CONTEXT B1.01

How many cells in a human body?

In some organisms, it is possible to count the number of cells in their bodies. In organisms such as humans, we can only estimate numbers. It would be impossible to count them all. Cells differ in their volume, mass and how closely or loosely they are packed together.

Scientists recently calculated the numbers of different cells and cell types in different organs and added them up.

This latest estimate suggests that the body of an adult human contains around 37 trillion cells – that is 37 000 000 000 000.

Discussion question

1 Can you think of any advantages for larger organisms of consisting of multiple cells, rather than just one larger cell?

KEY WORD

organism: a living thing.

ACTIVITY B1.01

Matching the characteristics of living things with their descriptions

Work in a group of four or five for this activity.

You will need:

- 14 pieces of blank card, all exactly the same.

1 Write the seven characteristics of living things on seven of the pieces of card.
2 Write descriptions of each of the seven characteristics on the other seven cards.
3 Shuffle each set of cards. Place them face down in two rows of seven.
4 One person then selects a card from each row and turns them face up. If the name and description match, this person keeps the two cards. If they do not match, they place them face down again in the same positions.
5 Now the next person does the same.
6 Keep taking turns until all the cards have been taken by someone. The winner is the person with most cards at the end.

Questions

B1.01 A student claimed that plants show fewer of the characteristics of living things than animals. Explain why this claim is wrong.

B1.02 Consider *two* organisms. For each, identify:

a the characteristics of living things that the organism carries out all the time

b the characteristics of living things that only happen at certain times.

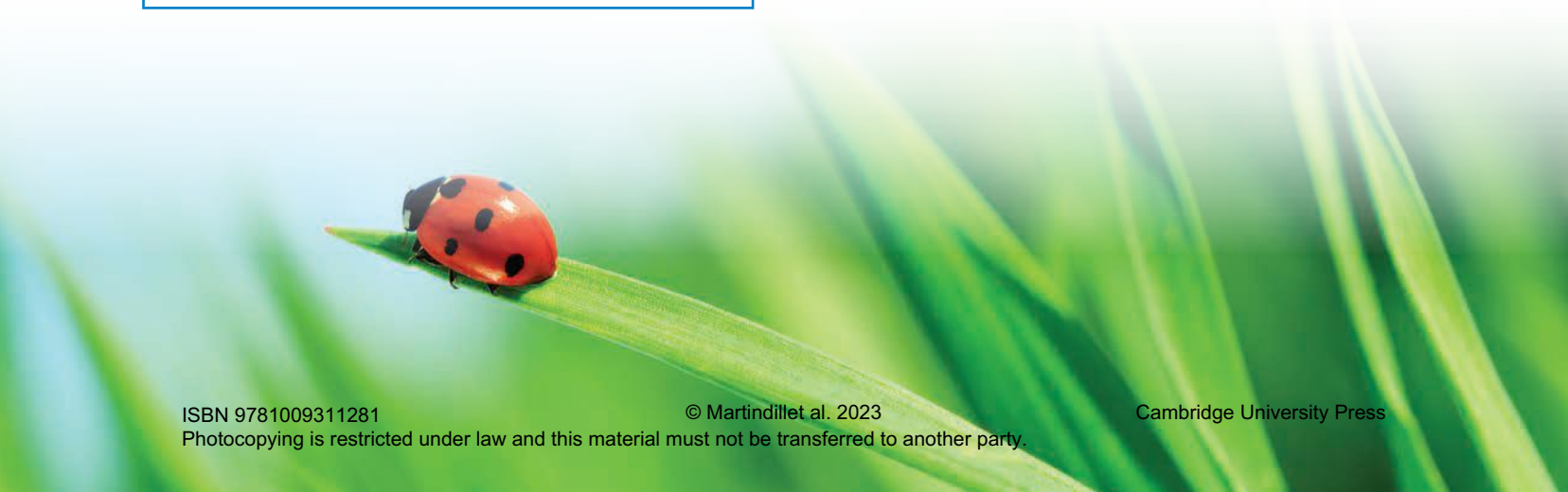
B1.02 Cell structure

All organisms are made of **cells**. Cells are very small, so large organisms contain millions of cells. They are multicellular. Some organisms are unicellular, which means that they are made of just a single cell. Bacteria and yeast are examples of single-celled organisms.

All cells are made from existing cells. New cells are formed when a fully grown cell divides. You can read about how cells divide in Chapter B12.

KEY WORD

cells: the smallest units from which all organisms are made.



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Microscopes

To see cells clearly, you need to use a microscope (Figure B1.02). The kind of microscope used in a school laboratory is called a light microscope. This is because it shines light through the piece of animal or plant you are looking at. It uses glass lenses to magnify and focus the image. A very good light microscope can magnify about 1500 times, so that all the structures in Figures B1.03 and B1.04 can be seen.

A photograph taken using a light microscope is called a photomicrograph. Figure B1.05 is a photomicrograph of some animal cells, and Figure B1.06 is a photomicrograph of some plant cells.

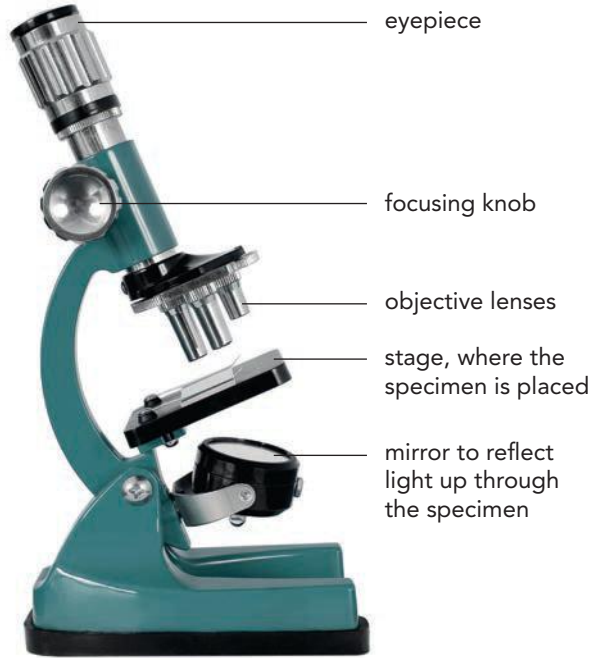

Figure B1.02: A light microscope.

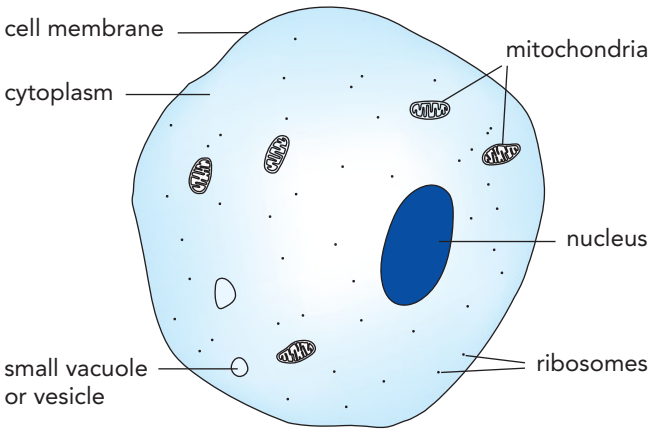

Figure B1.03: An animal cell as it appears through a light microscope.

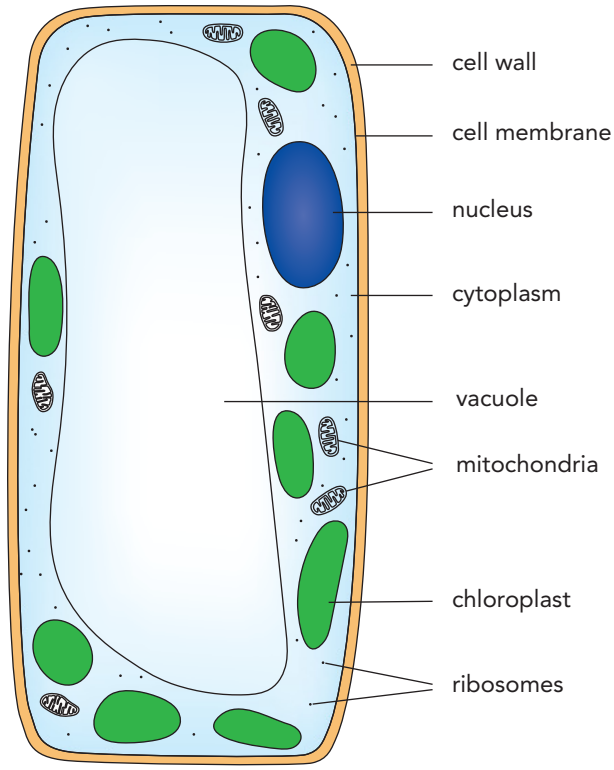

Figure B1.04: A plant cell as it appears through a light microscope.

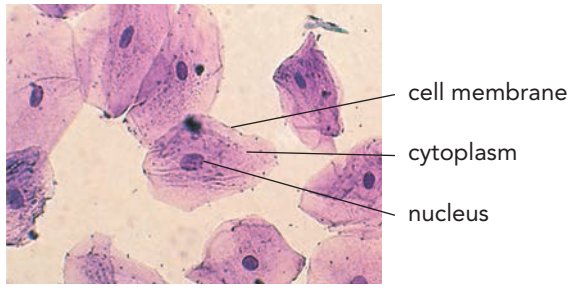

Figure B1.05: These are cells from the trachea (windpipe) of a mammal. They have been stained (coloured) with a dye that makes the nucleus look darker than the cytoplasm.

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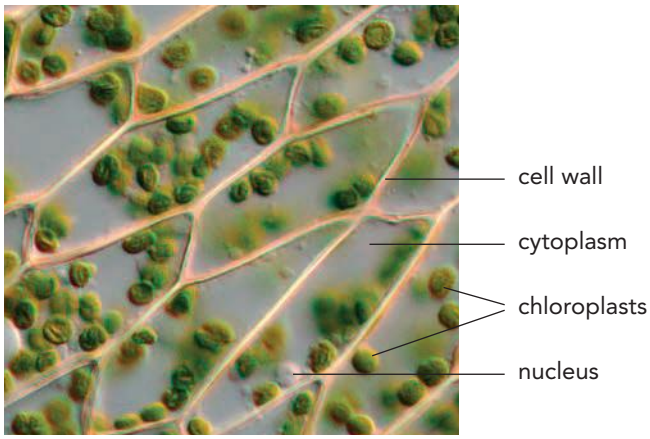

Figure B1.06: These are cells from a moss plant. You cannot see the cell membranes because they are pressed tightly against the inside of the cell walls.

Questions

B1.03 Explain the difference between a unicellular organism and a multicellular organism, giving *one* example of each.

B1.04 Look at the micrographs in Figures B1.05 and B1.06. Suggest why a stain has been added to the animal cells, but we can easily see the plant cells without using a stain.

Cell membrane

Every cell has a **cell membrane** around the outside. The cell membrane is a very thin layer of protein and fat. It is very important to the cell because it controls what goes in and out of it. It is **partially permeable**. This means that it will let some substances through but not others. The cell membrane separates the contents of the cell from its environment (surroundings).

It is difficult to see the cell membrane in a plant cell, because it is pressed tightly against the inside of the **cell wall**.

KEY WORDS

cell membrane: a very thin layer surrounding the cytoplasm of every cell; it controls what enters and leaves the cell.

partially permeable: allows some molecules and ions to pass through, but not others.

cell wall: a tough layer outside the cell membrane; found in the cells of plants, fungi and bacteria.

Cell wall

All plant cells are surrounded by a cell wall made mainly of cellulose. Animal cells never have cell walls.

Cellulose belongs to a group of substances called polysaccharides, which are described in Chapter B3. Cellulose forms fibres which criss-cross over one another to form a very strong covering to the cell (Figure B1.07). This helps to protect and support the cell. If the cell absorbs a lot of water and swells, the cell wall prevents it from bursting.

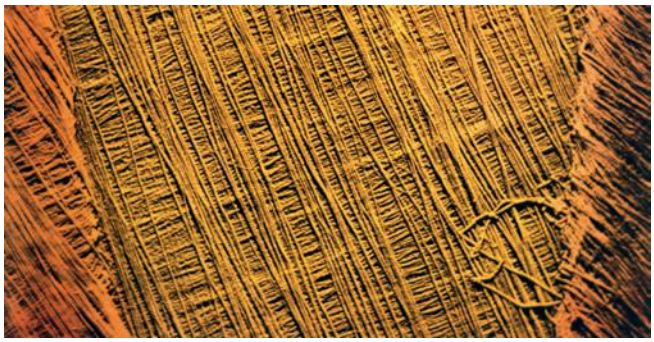

Figure B1.07: This photograph shows surfaces in three dimensions. You can see how the fibres of cellulose criss-cross over one another.

Because of the spaces between fibres, even very large molecules are able to go through the cellulose cell wall. It is **fully permeable**.

Cytoplasm

Cytoplasm is a clear jelly. It is nearly all water. It contains many substances dissolved in it, especially proteins. Many different **metabolic reactions** (the chemical reactions of life) take place in the cytoplasm.

KEY WORDS

fully permeable: allows all molecules and ions to pass through it.

cytoplasm: the jelly-like material that fills a cell.

metabolic reactions: chemical reactions that take place in living organisms.

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Vacuole

A **vacuole** is a fluid-filled space inside a cell which is surrounded by its own membrane. Plant cells have very large, permanent vacuoles, which contain a solution of sugars and other substances called **cell sap**. When the vacuole is full, it presses outwards on the rest of the cell, and helps it to keep its shape. Animal cells have much smaller vacuoles, called **vesicles**, which also contain solutions.

KEY WORDS

vacuole: a fluid-filled space inside a cell, separated from the cytoplasm by a membrane.

cell sap: the fluid that fills the large vacuoles in plant cells.

vesicle: a very small vacuole.

Nucleus

The **nucleus** (plural: nuclei) is where the genetic information is stored. The information is kept on the **chromosomes**, which are inherited from the organism's parents (Figure B1.08). The chromosomes are made of **DNA**. The information carried on the DNA determines the kinds of proteins that are made in the cell.

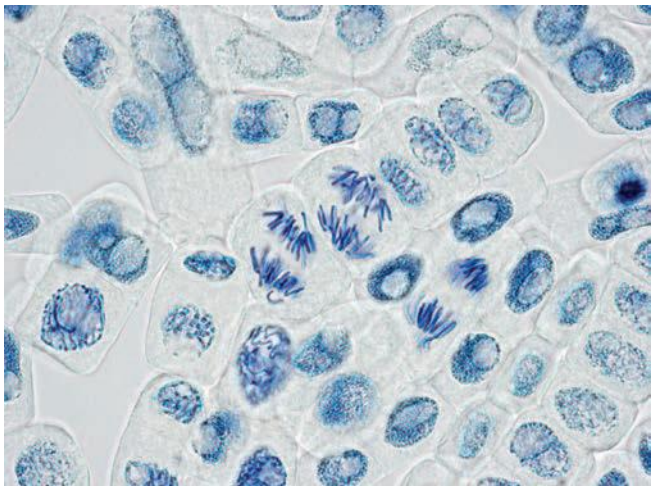

Figure B1.08: This photomicrograph shows some plant cells dividing. The nuclei of the cells have been coloured with a blue stain. The things that look like spider legs are chromosomes. We can normally only see chromosomes when a cell is dividing.

Chloroplasts

Chloroplasts are never found in animal cells, but most of the cells in the green parts of plants have them. They contain the green colouring, or pigment, called chlorophyll.

Chlorophyll absorbs energy from sunlight, and this energy is then used in making food for the plant by photosynthesis (Chapter B5). Chloroplasts often contain **starch grains**, which have been made by photosynthesis (Figure B1.09). Animal cells never contain starch grains.

Figure B1.09: This image shows a chloroplast from a cell in a pea plant. The large blue structure inside the chloroplast is a starch grain. The black stripes inside the chloroplast are membranes where the chlorophyll is kept.

KEY WORDS

nucleus: a structure containing DNA in the form of chromosomes.

chromosome: a length of DNA, found in the nucleus of a cell; it contains genetic information in the form of many different genes.

DNA: a molecule that contains genetic information, in the form of genes, that controls the proteins that are made in the cell.

chloroplasts: small structures found inside some plant cells, inside which photosynthesis takes place.

starch grains: structures that consist of thousands of starch molecules, stored in some plant cells.

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Mitochondria

All the structures we have looked at so far – cell membrane, cell wall, cytoplasm, vacuoles, nucleus and chloroplasts – can be seen with a good light microscope. But there are some smaller structures inside cells that we cannot see clearly unless we use an electron microscope. These include mitochondria (singular: **mitochondrion**).

Mitochondria are found in almost all plant and animal cells. Figure B1.10 is an electron micrograph of a mitochondrion, and Figure B1.11 shows what one might look like if we could cut it open and see it in three dimensions.

Mitochondria are the parts of the cell where **aerobic respiration** happens. This is how energy is released from glucose. You can read about aerobic respiration in Chapter B9.

Aerobic respiration is the main way in which cells get the energy that they need to stay alive. The more energy a cell needs, the more mitochondria it has. Muscle cells, for example, are packed full of mitochondria.

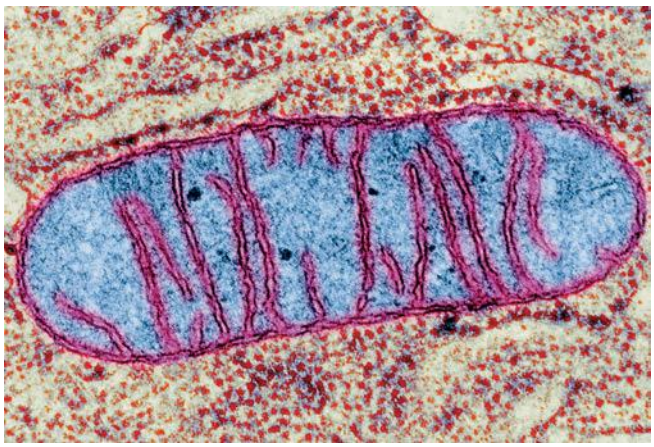

Figure B1.10: An electron micrograph of a mitochondrion. The pink lines are membranes, which separate the inside of the mitochondrion from the rest of the cell.

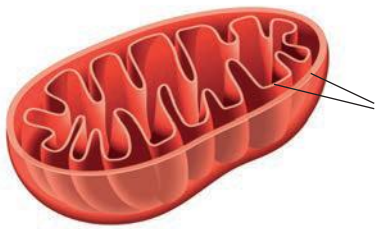

Figure B1.11: A drawing of a mitochondrion, cut open to show the membrane inside it.

Ribosomes

Ribosomes are tiny structures found in almost all animal cells and plant cells. They are so small that we can only see them with an electron microscope.

Ribosomes are where the cell makes proteins. The instructions on the DNA molecules are used to link together long chains of amino acids in a particular sequence. You can read more about protein molecules in Chapter B4, and more about how a cell makes them in Chapter B6.

Questions

B1.05 Name the part of a cell which has each of these functions:

- **a** makes proteins
- **b** contains the information for which proteins to make
- **c** photosynthesis
- **d** prevents the cell bursting when it takes up water
- **e** stores a solution of sugars and other solutes
- **f** controls what enters and leaves the cell.

B1.06 Which of the structures that you have named in Question B1.05 are found in both animal and plant cells?

KEY WORDS

mitochondrion: a small structure in a cell, where aerobic respiration releases energy from glucose.

aerobic respiration: chemical reactions that take place in mitochondria, which use oxygen to break down glucose and other nutrient molecules to release energy for the cell to use.

ribosome: very small structure in a cell that uses information on DNA to make protein molecules.

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ACTIVITY B1.02

Comparing animal cells and plant cells

Work in a group of three or four for this activity.

You are going to make a display to compare the structures of animal cells and plant cells.

Decide how you will do this. You could perhaps use annotated drawings, construct a large comparison table, or make a presentation.

You can use the information in this chapter to make your comparison. You might also like to look for some more pictures on the internet.

Bacterial cells

Bacteria (singular: bacterium) are unicellular organisms. Bacterial cells are rather different from the cells of animals and plants. Figure B1.12 is a diagram of a bacterium.

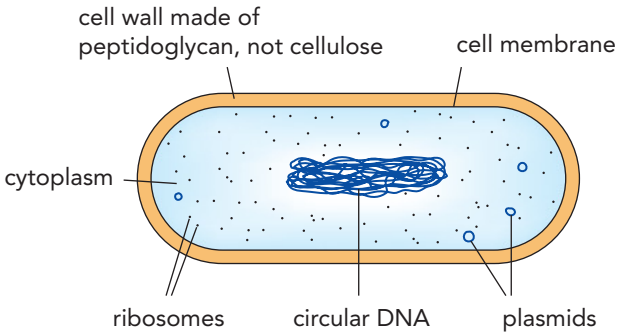

Figure B1.12: A bacterial cell.

Bacterial cells always have a cell wall. Unlike plant cells, this cell wall is not made of cellulose.

But the function is the same as in plant cells – the bacterial cell wall helps to support the cell, and prevents it from bursting if the cell takes up a lot of water.

A partially permeable cell membrane is pressed tightly against the inside of the bacterial cell wall.

As in plant and animal cells, the cell membrane controls what enters and leaves the cell.

Bacterial cells have cytoplasm and ribosomes.

These have the same functions as in animal and plant cells.

KEY WORD

bacteria: unicellular organisms whose cells do not contain a nucleus.

Bacterial cells do not have mitochondria or chloroplasts.

The most important difference between a bacterial cell and animal or plant cells is that bacteria do not have a nucleus. Bacterial cells are also known as **prokaryotic cells**. 'Pro' means 'before', and 'karyotic' means 'nucleus'. Prokaryotic cells appeared on Earth millions of years before cells with nuclei appeared.

Instead of chromosomes inside a nucleus, bacteria have a circle of DNA. This is sometimes called a bacterial chromosome.

The DNA has exactly the same function as in other cells – it provides instructions for making proteins.

Bacterial cells often have one or more smaller circles of DNA, called **plasmids**.

Scientists can use plasmids in the genetic modification of cells and organisms.

KEY WORDS

prokaryotic cells: cells with no nucleus; bacteria have prokaryotic cells.

plasmids: small, circular molecules of DNA, found in many prokaryotic cells in addition to the main, much larger circle of DNA.

Question

B1.07 Construct a table to compare the structure of a bacterial cell with animal and plant cells. Remember to include similarities as well as differences.

REFLECTION

How will you try to learn the names of the parts of animal, plant and bacterial cells, and their functions? Think about which of these ideas might work for you:

- looking at diagrams and reading about the structures
- practising drawing your own diagrams and labelling them
- getting a friend to test you by asking questions
- making some revision cards for yourself, with the name of a structure on one side and its function on the other side.

What other ideas might you try?

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B1.03 Specialised cells

Multicellular organisms, such as humans or plants, may contain vast numbers of cells. Not all of these cells are alike. For example, in a human body almost all of our cells have the same features that are found in most animal cells – a cell membrane, cytoplasm and a nucleus. But most of our cells have a particular function to perform, and their structure is modified to help them to carry out that function effectively. They are specialised. The same is true in a flowering plant, where all the cells have the basic characteristics of plant cells, but then have slightly different structures that relate to their specific functions.

You will meet many examples of specialised cells as you continue through your biology course. Table B1.01 lists seven of these (five from animals and two from plants) and indicates where you can find out more about each one.

Tissues

Often, cells that specialise in the same activity are found together. A group of cells like this is called a **tissue**. An example of a tissue is a layer of cells lining your stomach. These cells make enzymes to help to digest your food (Figure B1.13).

The stomach also contains other tissues. For example, there is a layer of muscle in the stomach wall, made of cells which can move. This muscle tissue makes the wall of the stomach move in and out, churning the food and mixing it up with enzymes.

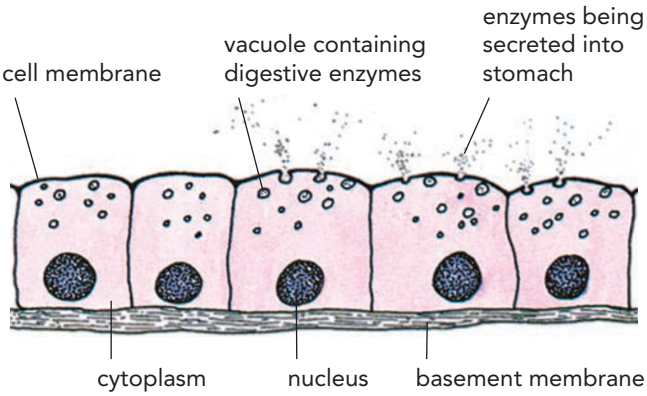

Figure B1.13: Cells lining the stomach – an example of a tissue.

Plants also have tissues. You may already have looked at some **epidermis** tissue from an onion bulb. Inside a leaf, a layer of cells makes up the palisade tissue. These cells are specialised to carry out photosynthesis.

KEY WORDS

tissue: a group of similar cells that work together to perform a particular function.

epidermis: the outer layer of tissue on a plant; also the outer layer of an animal's skin.

Specialised cell	Where it is found	Function	Where you can find out more
root hair cell	near the tips of the roots of flowering plants	absorption of water and mineral ions	Chapter B2
palisade mesophyll cell	in the leaves of flowering plants	photosynthesis	Chapter B5
red blood cell	in the blood of mammals	transporting oxygen	Chapter B7
ciliated cell	lining the trachea and bronchi of animals	cilia move mucus upwards	Chapter B9
neurone	in the nervous system of animals	conducting electrical impulses	Chapter B10
sperm cell	produced in the testes of mammals	the male gamete in sexual reproduction	Chapter B11
egg cell	produced in the ovaries of mammals	the female gamete in reproduction	Chapter B11

Table B1.01: Examples of specialised cells.

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Organs

A group of different tissues that carry out a function together is called an **organ**. The stomach is an organ. Other organs include the heart, the kidneys and the lungs. In a plant, an onion bulb is an organ. A leaf is another example of a plant organ.

The stomach is only one of the organs which help in the **digestion** of food. The mouth, the intestines and the stomach are all part of an **organ system** called the digestive system. The heart is part of the circulatory system, and each kidney is part of the excretory system.

The way in which organisms are built up can be summarised like this: cells make up tissues, which make up organs, which make up organ systems, which make up organisms.

B1.04 Sizes of specimens

Many of the structures that biologists study are very small. Cells, for example, are so small that we cannot see them without a microscope. The photographs and diagrams of cells in this chapter are all much larger than actual cells.

We can tell someone how much bigger the image is than the actual object by giving its **magnification**. The magnification of an object is how many times larger it is than the real object.

KEY EQUATION

$$\text{magnification} = \frac{\text{size of image}}{\text{size of actual object}}$$

There are two very important things to remember when you are calculating a magnification:

- Make sure that all the numbers in your calculation have the same units. It is often a good idea to convert everything to millimetres, mm, before you do anything else.
- Magnification is always written with a multiplication sign in front of it, ×. Magnification does not have units.

Some of the objects that we study in biology are so small that even millimetres are not a suitable unit to use for measuring them. Instead, we use micrometres. The symbol for a micrometre is µm.

$$1\,\mu m = 1 \times 10^{-6}\,m$$
$$1\,m = 10^{6}\,\mu m$$

KEY WORDS

organ: a structure made up of a group of tissues, working together to perform specific functions.

digestion: the breakdown of food.

organ system: a group of organs with related functions, working together to perform body functions.

magnification: how many times larger an image is than an object.

Questions

B1.08 How many micrometres are there in 1 mm?

B1.09 The mitochondrion in Figure B1.10 is magnified 20 000 times.

a Using a ruler, carefully measure the maximum length of the mitochondrion. Record your measurement in mm (millimetres).

b Convert your answer to µm (micrometres).

c Use this formula to calculate the real size of the mitochondrion in µm:

$$\text{Real size in } \mu m = \frac{\text{size of image in } \mu m}{\text{magnification}}$$

d How many of these mitochondria could you line up end to end between two of the mm marks on your ruler?

ACTIVITY B1.03

Practising using the magnification equation

Work on your own for the first part of this activity, and then pair up with someone else for the second part.

You will need:

- several small objects that are easy to measure and draw – for example, an eraser, a paper clip, a button
- a ruler that can measure in mm
- some plain paper, a sharp pencil and an eraser.

Part 1

Work on your own for this.

1 Measure each object carefully and write down the measurements. Do not let anyone else see these measurements at this point.

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CONTINUED

2 Make a magnified drawing of your objects. Calculate the magnification of each one and write it next to your drawings. Try to use different magnifications for each object. (You could even try drawing some objects smaller than they really are, so that the magnification is less than 1.)

Part 2

Work with a partner.

3 Exchange your drawings with a partner. Each of you now uses the drawings and magnifications to work out the size of the actual object.

4 Check your answers with your partner. Did you correctly calculate the actual sizes of the objects they had drawn? Did your partner calculate the actual sizes of the objects that you had drawn?

Self assessment

Did you calculate the magnifications of your drawings correctly, so that your partner could work out the actual size of each drawing?

If not, where did you go wrong?

Were you able to calculate the actual size of the objects your partner had drawn? If not, where did you (or they) go wrong?

Reflection

When you carried out your calculations, did you make any mistakes? What could you do to avoid making those mistakes next time? What can you do to help you to remember the equation and how to use it?

PROJECT B1.01 THE CHARACTERISTICS OF A NEW SPECIES

Each year, biologists discover new species. Some of these are small (e.g. insects, small plants) while others are surprisingly large (e.g. mammals, trees).

Work in a group of three or four. Use the internet to search for some examples of newly discovered species and select one to research in detail. Try to find one that has unusual features, or which was discovered in an extreme or hard-to-reach environment.

Decide how you will share the results of your research with others. For example, you could give an illustrated talk, or produce a poster. Decide how you will share out the tasks between you.

Try to find information about some or all of these issues:

- How did the scientists know that the species represents a living organism?
- How are some of the features of the seven characteristics of life of these species unusual compared to previously identified species?
- Where and how was the new species discovered? Why had it not been discovered before?
- Is anything known about the structure of its cells and how they are specialised?
- Biologists will want to find out more about the new species. However, if it is rare they will not want to take many specimens from the wild, or disturb it in its habitat. How have these conflicts been resolved?

Figure B1.14: The tree *Dinizia jueirana-facao* is a species that was recently discovered in Brazil.

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SUMMARY

All organisms show seven characteristics: movement, respiration, sensitivity, growth, reproduction, excretion and nutrition.
All organisms are made of cells. New cells are always made by the division of existing cells.
Animal and plant cells contain cytoplasm, a cell membrane, ribosomes, mitochondria and a nucleus containing DNA in the form of chromosomes. Plant cells also contain a cell wall, a large vacuole and sometimes chloroplasts.
Bacterial cells have cytoplasm, a cell membrane, a cell wall and ribosomes. They do not have a nucleus. Their DNA is circular. They may have extra, small circles of DNA called plasmids.
The cell membrane of all cells is partially permeable and controls what enters and leaves the cell. The cell wall is fully permeable and allows all molecules and ions to pass through it.
Ribosomes are the site of protein synthesis in a cell.
Mitochondria release energy from glucose and other nutrients, by aerobic respiration.
Chloroplasts are the site of photosynthesis.
Cells may be specialised for specific functions.
Magnification can be calculated using the equation $\text{magnification} = \frac{\text{size of image}}{\text{size of actual object}}$
Conversion from millimeters, to micrometers, μm.

PRACTICE QUESTIONS

1 **Identify** the characteristic which is *not* shown by all living organisms.

A excretion
B movement
C photosynthesis
D respiration **[1]**

2 The tongue-eating louse is a parasite of large fish. As its name suggests, it has an unusual way of gaining nutrition. It detects chemicals on the gills of a fish. From the gills it crawls into the fish's mouth. First, the louse sucks blood from the tongue. This causes the tongue to shrink and eventually fall off. Next, the louse takes the place of the tongue. Here the louse remains, feeding on food that the fish takes into its mouth.

a **Define** *nutrition*. **[2]**

b Apart from nutrition, **explain** how *two* features of the louse are characteristics of all living organisms. **[2]**

c The tongue-eating louse can reproduce.

i Define *reproduction*. **[2]**

ii **Suggest** *one* reason why scientists know very little about the process of reproduction in this species. **[1]**

[Total: 7]

COMMAND WORDS

identify: name/select/recognise.

define: give a precise meaning.

explain: set out purposes or reasons/make the relationships between things clear/say why and/or how and support with relevant evidence.

TIP

The mark allocation for a question will often indicate the number of points that you should make, in order to fully answer that question.

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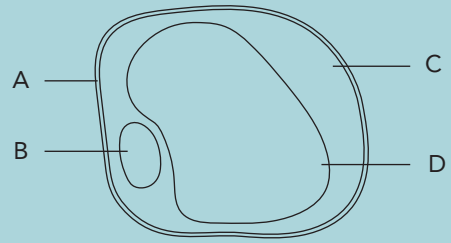
3 The diagram below shows a cell from a plant leaf.



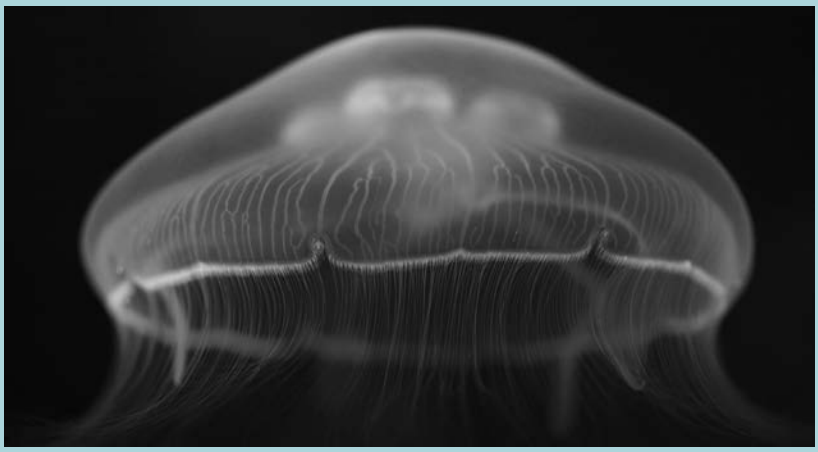
Identify which labelled part contains DNA. **[1]**

4 A diagram of a flower is 8 cm across. The magnification of the diagram is ×4.

Identify the actual width of the flower.

A 3.2 mm
B 20 mm
C 0.5 cm
D 32 cm **[1]**

5 The photograph shows a jellyfish. A jellyfish belongs to the animal kingdom.



a The actual jellyfish is 50 mm in diameter.

Calculate the magnification of the photograph. **[3]**

b **State** *three* parts that you would find in a cell in a jellyfish *and* outline the function of each part. **[6]**

[Total: 9]

COMMAND WORD

suggest: apply knowledge and understanding to situations where there is a range of valid responses in order to make proposals/put forward considerations.

COMMAND WORDS

calculate: work out from given facts, figures or information.

state: express in clear terms.

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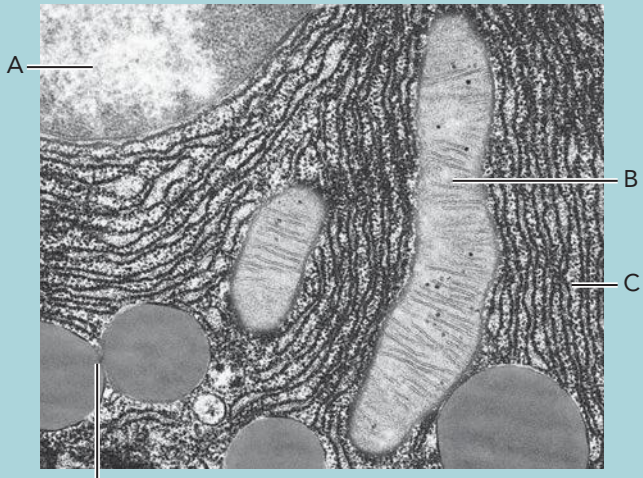
6 This is an electron micrograph of a small part of a cell from the pancreas. This cell makes large quantities of protein molecules, which are stored in vesicles before being exported from the cell.



a Structure A contains molecules that determine the type of proteins made in the cell. Identify structure A. **[1]**

b Use the information above to explain why the cell has large numbers of structures B and C. **[6]**

c State *one* way you can tell that these are not bacterial cells. **[1]**

[Total: 8]

SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
define the seven characteristics of living organisms	B1.01			
describe how all organisms are made of cells, and new cells are always made by the division of existing cells	B1.02			
describe and compare the structure of a bacterial cell, an animal cell, and a plant cell	B1.02			
describe the functions of each of the structures found in an animal cell and a plant cell	B1.02			

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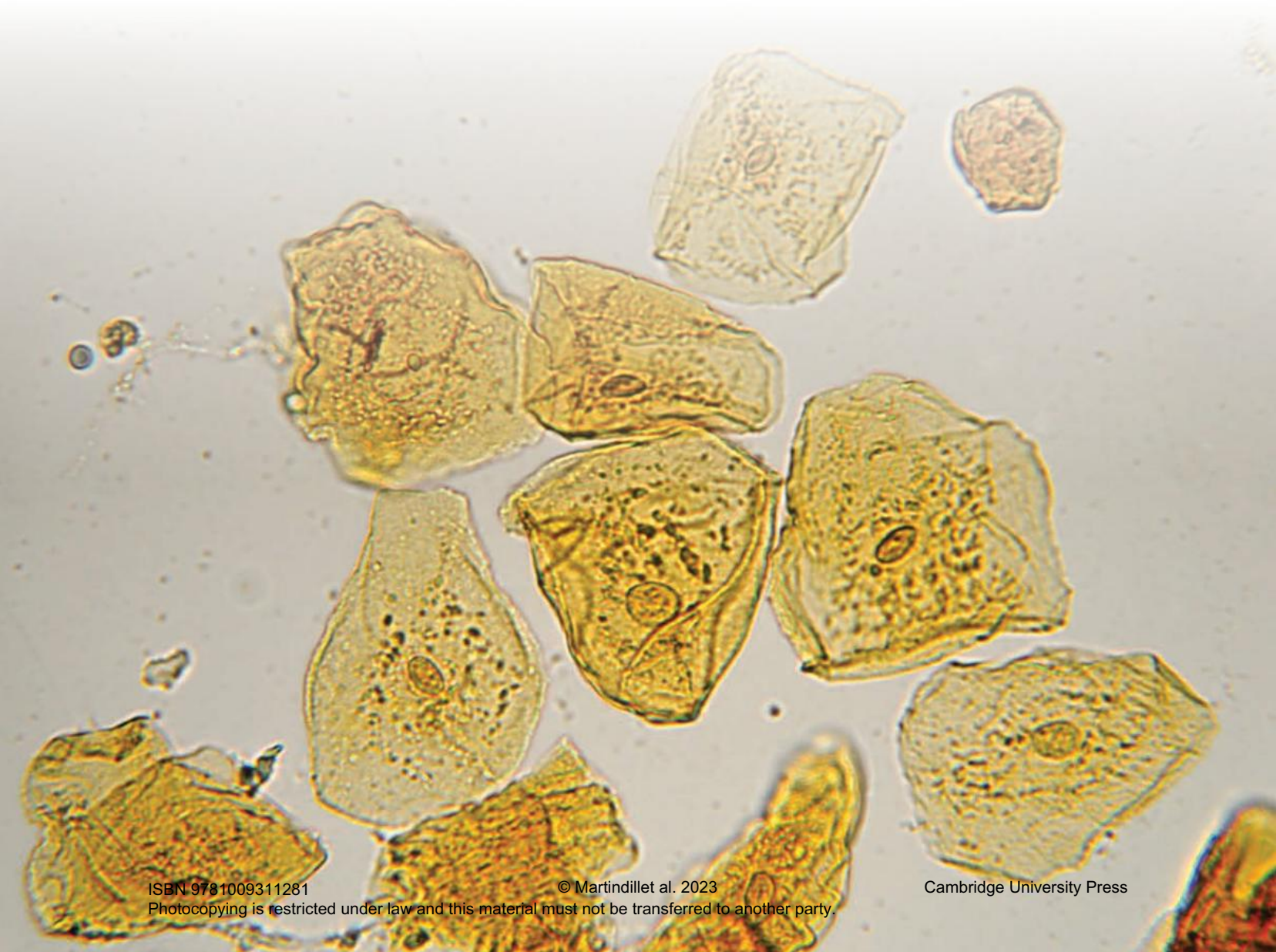
CONTINUED

I can	See topic . . .	Needs more work	Almost there	Confident to move on
describe the functions of each of the structures found in a bacterial cell	B1.02			
identify the parts of cells in diagrams, and in images taken using a light microscope or an electron microscope	B1.02			
name some specialised cells and their functions	B1.03			
calculate magnifications or actual sizes of objects shown in images	B1.04			
convert measurements between millimetres and micrometres.	B1.04			



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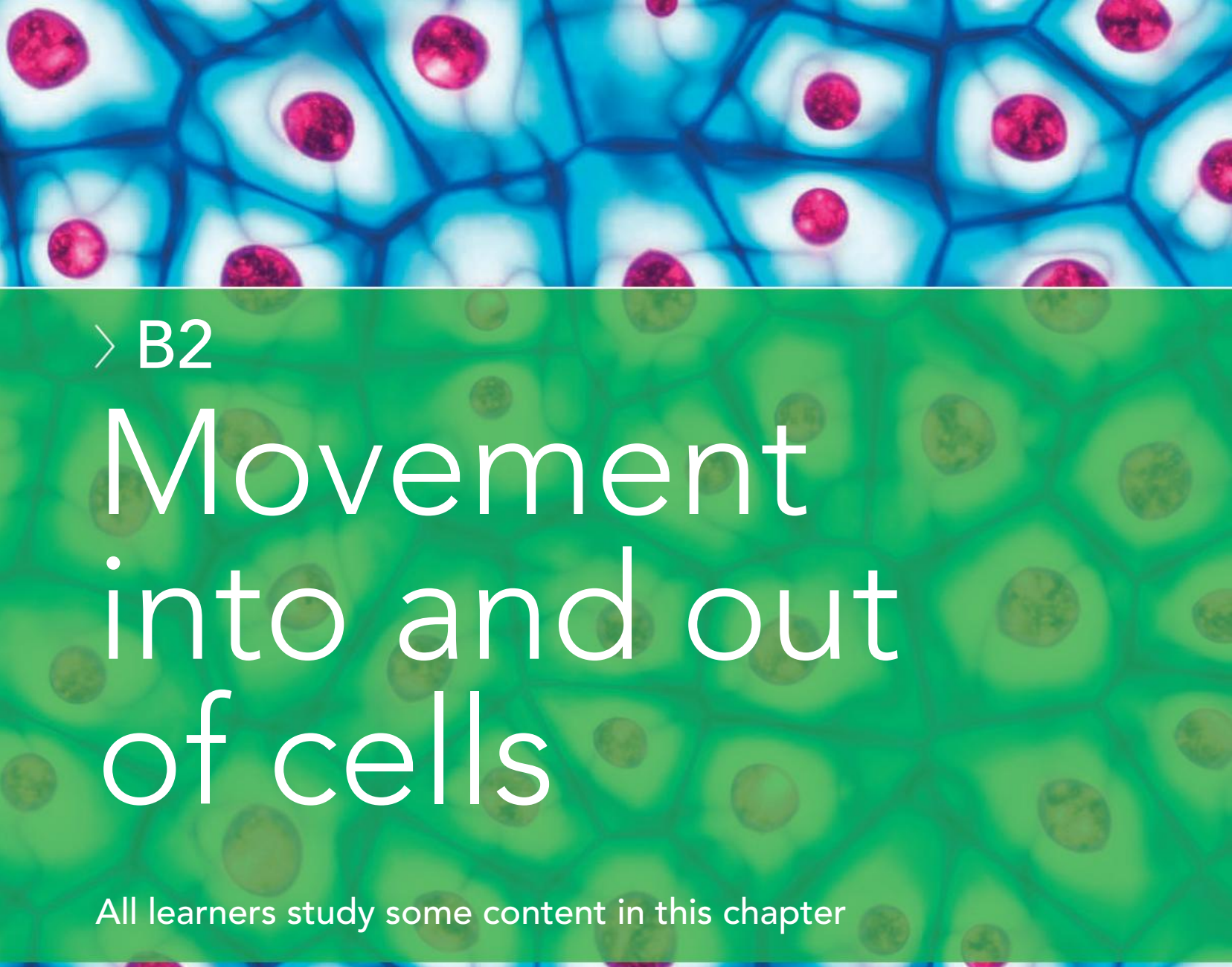

B2 Movement into and out of cells

All learners study some content in this chapter

IN THIS CHAPTER YOU WILL:

- learn about diffusion
- investigate factors that affect the rate of diffusion
- find out how osmosis is a special kind of diffusion, involving water
- investigate osmosis, using plant tissues
- learn about active transport
- learn about water potential
- explain how osmosis affects plant cells
- explain how active transport happens.

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BEFORE YOU START

The particle theory helps us to explain how matter behaves.

Here are six statements about particles. Some of them describe solids, some describe liquids and some describe gases. Which are which?

- The particles are far apart and rarely collide with each other.
- The particles vibrate on the spot.
- The particles are close to one another but can move around.
- The particles move freely in all directions.
- The particles stay in contact and slide past one another as they move.
- The particles are in fixed positions, close to one another.

SCIENCE IN CONTEXT B2.01

Filtering blood

We each have two kidneys. Their function is to remove unwanted substances from the blood. The kidneys produce a solution of the unwanted substances, which is removed from the body as urine.

However, sometimes kidneys stop working. When this happens, the unwanted substances build up in the blood. Some of these substances can be quite dangerous, so it is important to find another way to remove them.

The boy shown in Figure B2.01 is attached to a dialysis machine. The blood from a vein in his arm flows into the machine. Inside the machine, a liquid called dialysis fluid flows past his blood. There is a very thin membrane between his blood and the dialysis fluid. The unwanted substances in his blood diffuse through the membrane into the dialysis fluid, which then flows away. His cleaned blood flows back into his body. It takes several hours for all the unwanted substances to be removed from his blood, and he has to do this several times a week.

Figure B2.01: A patient undergoing dialysis.

Discussion questions

1 If the boy could have a kidney transplant, he would not have to spend time attached to a dialysis machine. Why do you think not everyone who needs a kidney transplant can have one?

2 The dialysis fluid flows constantly through the machine. Can you suggest why this works better than just having stationary fluid in the machine?

B2.01 Diffusion

Everything – including living cells – is made of atoms, molecules and ions. These **particles** are always moving. This helps to explain a process called **diffusion**.

When they can move freely, particles tend to spread themselves out evenly. This happens with gases, solutions and mixtures of liquids.

Imagine, for example, a rotten egg full of hydrogen sulfide gas in one corner of a room. Hydrogen sulfide gas is *very* smelly. To begin with, there is a high concentration of the gas near the egg but none in the rest of the room (Figure B2.02). The hydrogen sulfide molecules quickly spread through the air in the whole room. Soon, you cannot tell where the smell first came from because the whole room smells of rotten egg!

KEY WORDS

particles: (in this context) the smallest pieces of which a substance is made; particles can be molecules, atoms or ions.

diffusion: the net movement of particles from a region of their higher concentration to a region of their lower concentration (i.e. down a concentration gradient), as a result of their random movement.

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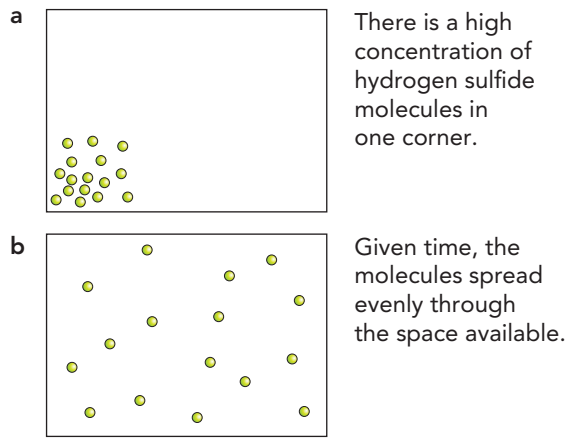

Figure B2.02: The random movements of gas molecules result in them spreading evenly through all the space available.

The hydrogen sulfide molecules have spread out through the air. This spreading out is called diffusion. Diffusion happens because the molecules move randomly. They do not purposefully move from one place to another. Each molecule just moves by chance, changing direction when it bumps into another molecule. Some molecules might even go back into the rotten egg again. But, overall, the molecules spread fairly evenly across the room.

We call this the **net movement** of the molecules. Some go from the egg into the room, and a few from the room back into the egg – but overall, most of them go from the egg into the room.

A place where a lot of the molecules are quite close together has a high concentration of molecules. In this example, the rotten egg had the highest concentration of hydrogen sulfide molecules. The rest of the room had a low concentration of hydrogen sulfide molecules. Overall, the random movements of the molecules caused them to spread out evenly throughout all of the space they could get to.

One way of thinking about this is to imagine a slope (see Figure B2.03). The place with the high concentration (the rotten egg) is at the top of the slope. The place with the low concentration (the rest of the room) is at the bottom of the slope. The molecules move 'down the slope' from where there is a high concentration of molecules to where there is a low concentration. Another word for 'slope' is 'gradient'. We can therefore say that there is a **concentration gradient** from the rotten egg to the rest of the room. The overall result of diffusion is that the hydrogen sulfide molecules move 'down' this concentration gradient.

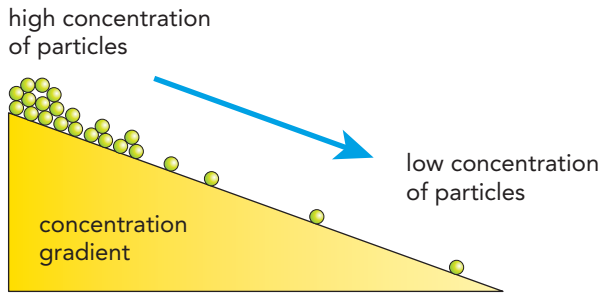

Figure B2.03: This diagram shows how we can use the analogy of a slope to think about a concentration gradient. We can imagine particles moving down the slope, from a high concentration to a low concentration.

KEY WORDS

net movement: overall or average movement.

concentration gradient: an imaginary 'slope' from a high concentration to a low concentration.

ACTIVITY B2.01

Modelling diffusion

In this activity, you will model diffusion using people to represent particles.

You will need:

- a fairly big, empty space to move around in, such as a playground or a large hall.

Method

Work as a whole class for this activity.

Each person in the class represents a particle in a gas.

Start with most people in one corner of the room or space. Do not crowd too closely – remember that gas particles do not touch one another. Face any way that you like.

Each person now starts to move in a straight line in the direction they are facing. (Real gas particles move very quickly, but it is best if you do not move too fast, or there might be uncomfortable collisions.)

Keep going in your straight line until you hit something. This might be another particle, or it might be the wall of your 'container'. When you collide, change direction and keep going in your new straight line.

Continue doing this for a few minutes. Then stop and look around you.

Questions

1 What has happened to the 'particles'? Are they still concentrated in one corner?

2 Try to explain why this has happened.

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CONTINUED

Reflection

You have now used two different models of diffusion. The first one was the picture of a slope in Figure B2.03, and the second model used moving people to represent particles. Which one of these models best helped you to understand diffusion? Why?

Questions

B2.01 Look at the definition of diffusion in the 'Key words' box at the start of this section.

Explain why the following conditions are required for diffusion to occur:

- **a** movement of particles
- **b** a concentration gradient
- **c** random movement.

B2.02 When substances diffuse into and out of cells, which part of the cell must they move through?

Diffusion can occur at different rates (speeds). How fast particles move from an area of high concentration to low concentration depends upon:

- Temperature. Particles have more kinetic energy at a high temperature, so their random movement will be quicker and diffusion is faster.
- Surface area. If there is a greater area over which particles can move from one place to another, diffusion will be faster.
- Concentration gradient. If there is a large difference in concentration between two areas, diffusion will take place quickly. This is because although particles will move randomly towards the area of low concentration, fewer will move randomly in the opposite direction.
- Diffusion distance. If the thickness of the membrane through which particles move is small, diffusion will be faster.

It is possible to investigate the effect of these four factors on the rate of diffusion in the laboratory.

EXPERIMENTAL SKILLS B2.01

Investigating how surface area affects diffusion

In this investigation, you will use pieces of agar jelly to represent cells. You will follow instructions to investigate how the surface area of the 'cells' affects the diffusion of a substance through them.

CONTINUED: B2.01

You will need:

- a dish containing agar jelly, made with a small amount of a weak alkali such as ammonium hydroxide, and coloured with a dye called cresol red
- a sharp knife to cut the jelly into pieces
- some plastic or blunt-ended forceps (tweezers)
- a ruler to measure in mm
- two large test-tubes or other large glass tubes, more than 1 cm in diameter
- a stopwatch
- some dilute hydrochloric acid.

Safety

Take care with the acid. Wear safety glasses in case of splashes. If you spill the acid, clean up the spills immediately, using plenty of cold water.

Take care with the sharp blade. Cut with the blade facing away from you. Place the jelly on a firm surface before you start to cut it.

Method

1. Cut two cubes of agar jelly, with sides of 1 cm.
2. Cut one of the cubes into eight smaller cubes, each with sides of 0.5 cm.
3. Put the large cube into a test-tube. Put the eight small cubes into the other test-tube.
4. Add equal volumes of dilute hydrochloric acid to each tube, making sure that all of the cubes are covered with acid.
5. Start the stopwatch. Time how many seconds it takes for the cubes in each test-tube to become fully yellow.

Questions

1. The jelly cubes contained a weak alkali and cresol red, which is an indicator. Explain why the cubes changed colour.
2. How did the total volume of the eight small cubes compare with the volume of the one larger cube? Was it greater, smaller, or the same?
3. How did the total surface area of the eight small cubes compare with the surface area of the one larger cube? Was it greater, smaller, or the same?
4. Copy and complete these sentences, choosing the correct words.

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CONTINUED: B2.01

The time taken for the eight small cubes to completely change colour was **longer/shorter** than the time for the one single cube.

This is because the **surface area/volume** of the small cubes was **greater/smaller** than that of the single cube.

5 Write a conclusion for your experiment. Include the words diffusion and surface area in your conclusion.

EXPERIMENTAL SKILLS B2.02

Investigating how temperature, concentration gradient or distance affect diffusion

In the previous experiment, you used cubes of alkaline agar jelly and an indicator, so that you could measure the time taken for an acid to diffuse through the cubes. Now you are going to plan how you can use this technique to investigate other factors. You may be able to carry out the experiment that you plan.

Questions

1 As well as surface area, diffusion is also affected by:

- temperature
- concentration gradient
- distance.

Choose one of these variables to investigate.

2 The variable that you change in your experiment is called the **independent variable**. What is the independent variable in your experiment?

3 Think about how you can change your independent variable. Decide how many different values you will have.

4 The variable that you measure, as you collect your results, is the **dependent variable**. What is the dependent variable in your experiment?

5 Describe how you will measure your dependent variable.

6 It is important that no variables, other than the one you are investigating, affect your experiment. Which variables will you standardise (keep the same) in your experiment? How will you do this?

7 Write a short, clear description of how you will do your experiment.

8 Draw a results chart that you could use to fill in your results. Include headings, but do not put in any results (unless you are able to actually do your experiment, of course).

CONTINUED: B2.02

9 Predict what you would expect to find in your experiment.

KEY WORDS

independent variable: the variable that you change in an experiment.

dependent variable: the variable that you measure, as you collect your results.

B2.02 Osmosis

Every cell in an organism's body has water inside it and outside it. Many different substances are dissolved in this water, and their concentrations may be different inside and outside the cell. This creates concentration gradients, down which water and solutes will diffuse, if they are able to pass through the membrane.

It is easiest to think about this if we consider a simple situation involving just one solute. Figure B2.04 illustrates a concentrated sugar solution, separated from a dilute sugar solution by a membrane. The membrane has holes, or pores, in it. These pores are very small.

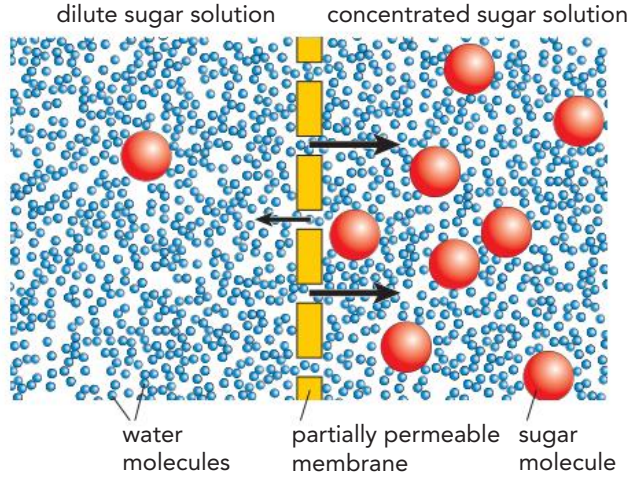

Figure B2.04: How osmosis happens. It is important to think about the diffusion of each kind of molecule separately.

Water molecules are also very small. Each one is made of two hydrogen atoms and one oxygen atom. Sugar molecules are many times larger than this.

In many membranes, the holes are big enough to let the water molecules through, but not the sugar molecules.

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These are partially permeable membranes because they will let some molecules through but not others.

There is a higher concentration of sugar molecules on the right-hand side of the membrane in Figure B2.04, and a lower concentration on the left-hand side. If the membrane was not there, the sugar molecules would diffuse from the concentrated solution into the dilute one until they were evenly spread out. However, they cannot do this because the holes in the membrane are too small for them to get through.

There is also a concentration gradient for the water molecules. On the left-hand side of the membrane, there is a high concentration of water molecules. On the right-hand side, the concentration of water molecules is lower because a lot of space is taken up by sugar molecules.

Because there are more water molecules on the left-hand side, at any one moment more of them will 'hit' a hole in the membrane and move through to the other side than will go the other way (right to left). Over time, there will be an overall, or net, movement of water from left to right. This is called **osmosis**.

You can see that osmosis is really just a kind of diffusion. It is the diffusion of water molecules in a situation where the water molecules, but not the solute molecules, can pass through a membrane.

Water potential

It can be confusing to talk about the 'concentration' of water molecules, because the term *concentration* is normally used to mean the concentration of the solute dissolved in the water. It is much better to use a different term. We say that a dilute solution (where there is a lot of water) has a **high water potential**. A concentrated solution (where there is less water) has a **low water potential**.

In Figure B2.05, there is a high water potential on the left-hand side and a low water potential on the right-hand side. There is a **water potential gradient** between the two sides.

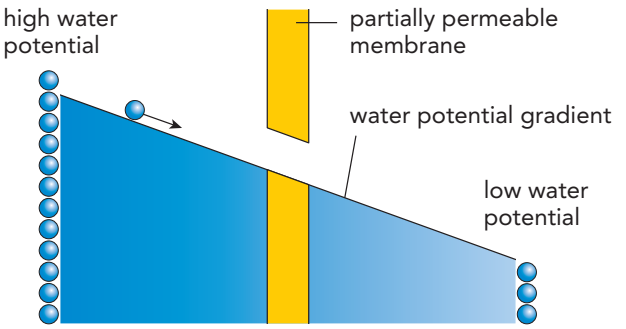

Figure B2.05: We can think of a water potential gradient as a 'slope'. Water molecules have a tendency to move down the slope, from a high water potential to a low water potential.

The water molecules diffuse down this gradient, from a high water potential to a low water potential.

Water potential and osmosis are very important to organisms because they affect how and when organisms take up water. You will find out about the uptake of water by plants in Chapter B7. The uptake of water by humans is described in Chapter B6.

KEY WORDS

osmosis: the diffusion of water molecules through a partially permeable membrane.

osmosis (in terms of water potential): the net movement of water molecules from a region of higher water potential (dilute solution) to a region of lower water potential (concentrated solution) through a partially permeable membrane.

high water potential: an area where there are a lot of water molecules, that is, a dilute solution.

low water potential: an area where there are not many water molecules, that is, a concentrated solution.

water potential gradient: a difference in water potential between two areas.

Questions

These questions are about the diagram in Figure B2.04.

B2.03 What is the solvent in the sugar solution? What is the solute?

B2.04 Explain why water molecules can move from one side of the membrane to the other, but sugar molecules cannot.

B2.05 In which direction is the net movement of water molecules?

B2.06 In Figure B2.04, which solution has the higher water potential? Explain your answer.

Osmosis and animal cells

You have seen that osmosis happens when two solutions (or a solution and pure water) are separated from each other by a partially permeable membrane. The membrane lets water molecules through, but not the other molecules that are dissolved in the water.

Cell membranes are partially permeable. They let water through easily, but other molecules and ions often cannot get through. This means that osmosis happens across cell membranes.

Figure B2.06 shows an animal cell in pure water. The cytoplasm inside the cell is a fairly concentrated solution. The proteins and many other substances dissolved in it are too large to get through the cell membrane. However, water molecules can get through the membrane.

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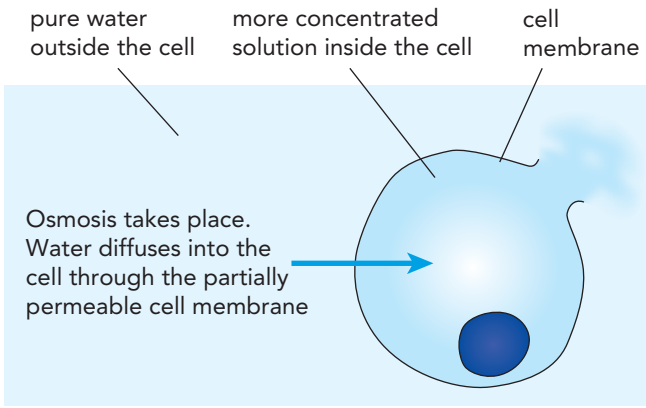

Figure B2.06: If an animal cell is placed in pure water, water enters the cell by osmosis. The cell swells and bursts.

If you compare this situation with Figure B2.04, you will see that they are similar. The dilute solution in Figure B2.04 and the pure water in Figure B2.06 are each separated from a concentrated solution by a partially permeable membrane. In Figure B2.06, the concentrated solution is the cytoplasm and the partially permeable membrane is the cell membrane. Therefore, osmosis will occur.

Water molecules will diffuse from the dilute solution into the concentrated solution. As more and more water enters the cell, it swells. The cell membrane has to stretch as the cell gets bigger, until eventually the strain is too much, and the cell bursts.

Figure B2.07 shows an animal cell in a concentrated solution. If this solution is more concentrated than the cytoplasm, then water molecules will diffuse out of the cell. Look at Figure B2.07 to see why. As the water molecules go out through the cell membrane, the cytoplasm shrinks, so the cell gets smaller.

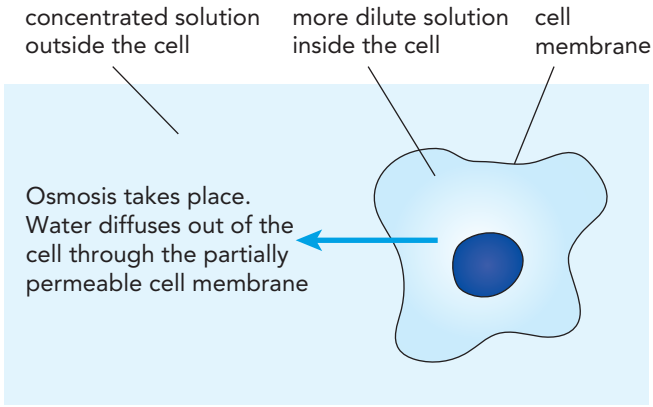

Figure B2.07: If an animal cell is placed in a concentrated solution, water leaves the cell by osmosis. The cell shrinks.

Osmosis and plant cells

Plant cells do not burst in pure water. Figure B2.08 shows a plant cell in pure water. Plant cells are surrounded by a cell wall. This is fully permeable, which means that it will let any molecules go through it.

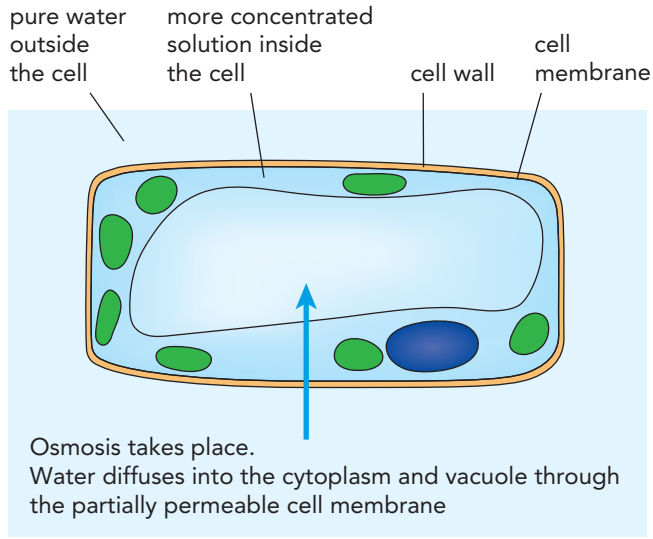

Figure B2.08: If a plant cell is placed in pure water, water enters the cell by osmosis. The cell swells but does not burst, because it has a strong cell wall.

Although it is not easy to see, a plant cell also has a cell membrane just like an animal cell. The cell membrane is partially permeable. A plant cell in pure water will take in water by osmosis through its partially permeable cell membrane in the same way as an animal cell. As the water goes in, the cytoplasm and vacuole will swell.

However, the plant cell has a very strong cell wall around it. The cell wall is much stronger than the cell membrane and it stops the plant cell from bursting. The cytoplasm presses out against the cell wall, but the wall resists and presses back on the contents.

In a plant leaf, cells that have plenty of water are all in this state. In each one, the cytoplasm presses out on the cell walls. The pressure of the water pushing outwards on the cells' walls keeps the whole group of cells strong and firm. This helps to support plant leaves.

A plant cell in this state is rather like a blown-up tyre – tight and firm. It is said to be **turgid**. The pressure of the water pushing outwards on the cell wall is called **turgor pressure**. Turgor pressure helps a plant that has no wood in it to stay upright, and keeps the leaves firm. Plant cells are usually turgid.

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KEY WORDS

turgid: a description of a plant cell that is tight and firm.

turgor pressure: the pressure of the water pushing outwards on a plant cell wall.

Now imagine that a plant cell is placed in a solution that is more concentrated than its cytoplasm. Water leaves the cell by osmosis. The cytoplasm and vacuole shrink. But the cell wall is strong and stays in position. The cytoplasm therefore pulls away from the cell wall. This pulls the membrane away from the cell wall, too. The cell now looks like the diagram in Figure B2.09 and the photographed cells in Figure B2.10.

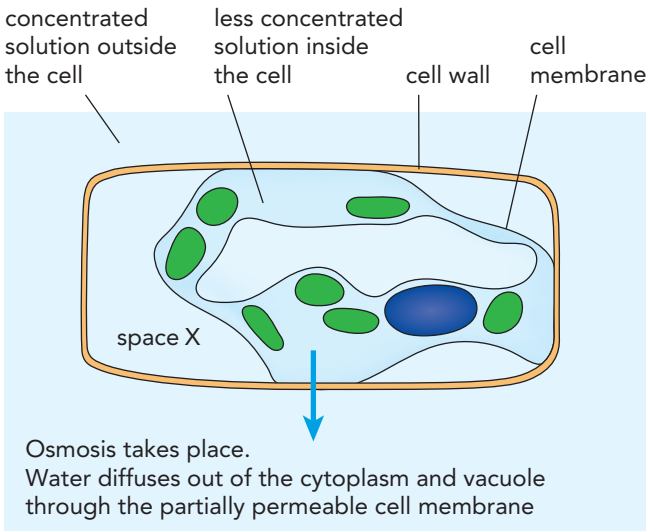

Figure B2.09: If a plant cell is placed in a concentrated solution, water moves out of it by osmosis. The cytoplasm and vacuole shrink, and the cell membrane pulls away from the cell wall.

When a plant cell loses a lot of water, it also loses its turgor pressure. The contents of the cell do not push outwards on the cell wall, so the cell becomes soft and floppy. It is said to be **flaccid**. If the cells in a plant become flaccid, the plant loses its firmness and begins to wilt.

When the cell membrane tears away from the cell wall, the cell is said to be **plasmolysed**. Plasmolysis can kill a plant cell because the cell membrane is damaged as it tears away from the cell wall.

KEY WORDS

flaccid: a description of a plant cell that has lost its turgor pressure and is soft.

plasmolysed: a description of a cell in which the cell membrane tears away from the cell wall.

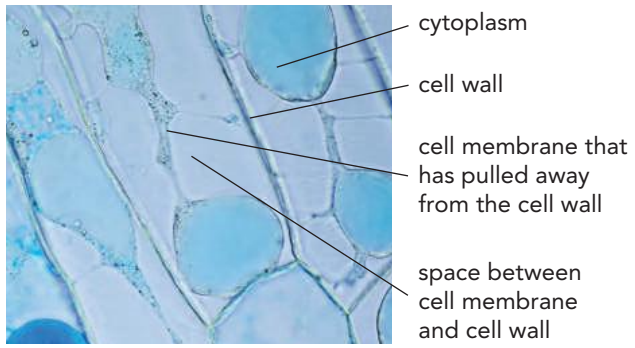

Figure B2.10: These onion cells have been placed in a concentrated solution. The cytoplasm has lost so much water, and shrunk so much, that it has pulled away from the cell wall.

Questions

B2.07 Copy and complete this sentence:
When an animal cell is placed in pure water, water _____ the cell by _____ through the partially permeable cell _____.

B2.08 Animal cells burst if they are placed in pure water, but plant cells do not. Explain why.

B2.09 Here are some descriptions of what happens to a plant cell when it is placed in a concentrated solution. They are in the wrong order. Write the descriptions in the correct order.

- The cytoplasm and vacuole shrink.
- The cell membrane is pulled away from the cell wall.
- Water moves out of the cell through the partially permeable cell membrane.

B2.10 Look at Figure B2.09. What fills space X? Explain your answer.

B2.11 A group of plant cells has been placed in a concentrated solution, and the cells are plasmolysed. Predict what will happen if the cells are now placed in pure water. Explain your answer, using the term water potential.

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EXPERIMENTAL SKILLS B2.03

Investigating the effect of osmosis on potato strips

In this investigation, you will place pieces of plant tissue into different solutions and measure the effect on their length.

You will need:

- a large potato
- a sharp knife or other way to peel the potato
- a cork borer to cut cylinders from the potato (or you can use the knife to cut strips)
- a ruler to measure in mm
- three containers such as small beakers
- some distilled water, a dilute sugar solution and a concentrated sugar solution.

Safety

Take care when using the sharp knife or potato peeler.

Method

1 Peel the potato. Use a cork borer to cut six cylinders from the potato. Cut the ends from each cylinder so that each one is the same length – 40 mm is a good length to use. Record this length. If you do not have a cork borer, you can cut rectangular pieces from the potato instead (see Figure B2.11).

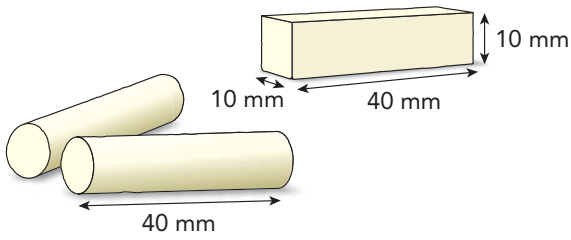

Figure B2.11: You can cut either cylinders or rectangular blocks from the potato.

2 Pour the distilled water into one beaker, and the two sugar solutions into the other two beakers. Label each beaker with the concentration of the solution.

3 Place two potato strips into each liquid, making sure they are completely covered.

4 Leave the potato strips in their liquids for about 20 minutes. While you are waiting, construct a results chart. You can fill in the original lengths of the strips.

5 After 20 minutes, take the potato strips out of their solutions. Measure the length of each one again. Record the new lengths.

6 Calculate the change in length of each strip. Remember to say whether it has got longer (a positive change) or shorter (a negative change).

Questions

1 What happened to the length of the potato strips that were placed in the distilled water?

2 Use your knowledge of osmosis to explain why this happened.

3 What happened to the length of the potato strips that were placed in the concentrated solution?

4 Use your knowledge of osmosis to explain why this happened.

Peer assessment

When you have completed your results table, exchange it with a partner.

Look at your partner's work, and give them a score for each of the following features:

2 marks Really good

1 mark Quite well done

0 marks Not done at all, or very poor

- The results table is drawn with a ruler.
- There are clear headings for all the columns, with units.
- There are no units written anywhere except in the headings.
- It is really easy to understand the results table.
- The changes in length are shown in the results table.
- The changes in length have been correctly calculated, and say whether the strips increased or decreased in length.

Add up the marks you will give to your partner. If you have not given them full marks, make sure you can explain why.

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B2.03 Active transport

There are many occasions when cells need to take in substances which are only present in small quantities around them. If the substance has a lower concentration outside the cell than inside, then we would expect the substance to diffuse out of the cell.

If the cell needs this substance, then it has to do something to make it go into the cell instead of diffusing out of it. Cells can use energy to make substances move across their membranes, up the concentration gradient. This process is called **active transport**. The energy needed to do this is provided by respiration. Aerobic respiration, in mitochondria in the cell, releases energy for the cell to use. Some of this energy is used for active transport, moving substances against their concentration gradients.

KEY WORDS

active transport: the movement of molecules or ions through a cell membrane from a region of lower concentration to a region of higher concentration (i.e. against a concentration gradient) using energy from respiration.

In plants, for example, root hair cells take in nitrate ions from the soil. The concentration of nitrate ions inside the root hair cell is usually higher than the concentration of nitrate ions in the soil. The diffusion gradient for the nitrate ions is out of the root hair, and into the soil. But the root hair cells are still able to take nitrate ions in, using active transport. Figure B2.12 shows how they do this.

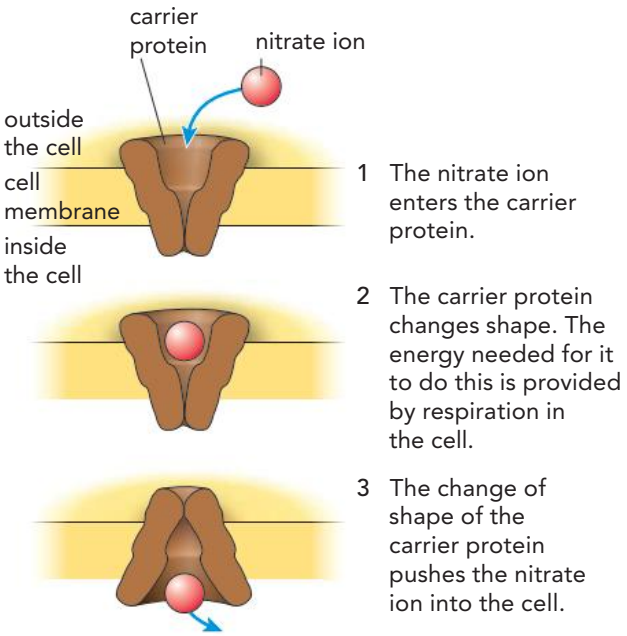
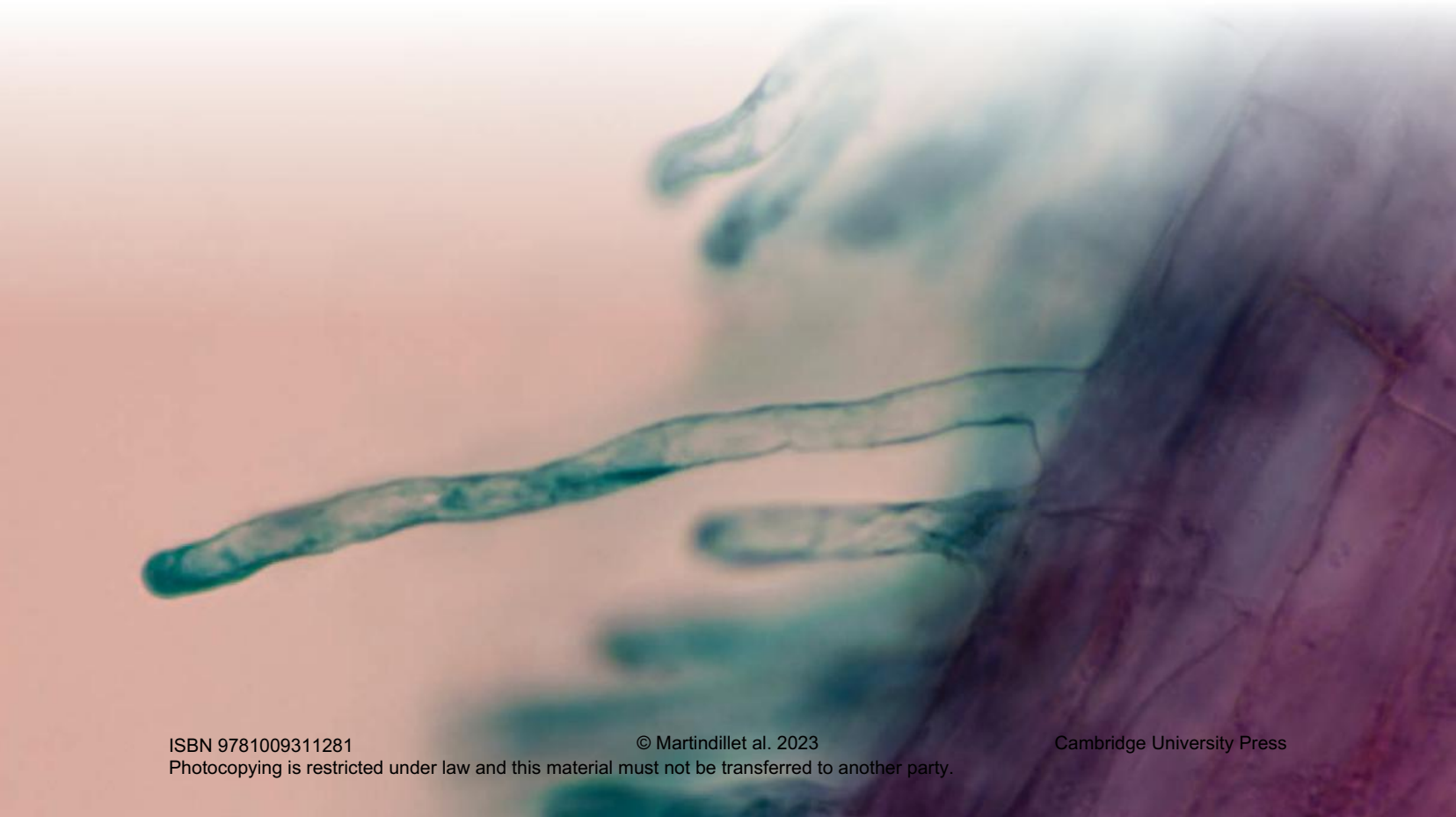


Figure B2.12: How active transport happens.



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There are special **carrier proteins** in the cell membrane of the root hair cells. These proteins pick up nitrate ions from outside the cell, and then change shape so that they push the nitrate ions through the cell membrane and into the cytoplasm of the cell. Energy is needed to produce the change of shape in the carrier protein. This energy is provided by the mitochondria, which carry out aerobic respiration.

KEY WORDS

carrier proteins (or protein carriers): protein molecules in cell membranes that can use energy to change shape and move ions or molecules into or out of a cell.

PROJECT B2.01 MAKING A GOOD CUP OF TEA

Tea leaves are dried leaves from a camellia plant (*Camellia sinensis* is the tea plant). When hot water is added to tea leaves, colour and flavour molecules diffuse out of the tea leaves and into the water.

You are going to investigate some factors that make a really good cup of tea.

Here are some ideas for questions to investigate. You might also think of some questions of your own.

- Does the temperature of the water affect the rate at which the molecules diffuse out of the tea bag?
- Does the temperature of the water affect the flavour of the tea?
- Do different kinds of tea bag affect the diffusion of substances out of the tea leaves and into the water?
- Does adding milk to the cup before you add the water affect the diffusion of molecules out of the tea leaves?

Work in a group of three or four.

Start by deciding on a question to investigate. Then plan how you will do your experiment. Remember to change only one variable – your independent variable. Think carefully about how you will measure your dependent variable, and how you will try to standardise other variables.

You could try to predict the results you would expect to get. Think about how you will record them, and how you will use them to answer the question you are investigating.

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SUMMARY

Diffusion is the net movement of molecules or ions from a high concentration to a lower concentration, as a result of their random movement and kinetic energy.
Oxygen and carbon dioxide enter and leave cells by diffusion through the cell membranes, down a concentration gradient.
An increase in temperature, concentration gradient or surface area speeds up diffusion into a cell. This can be investigated using pieces of agar jelly.
Water diffuses through partially permeable membranes, including cell membranes, by osmosis.
A solution containing a lot of water has a high water potential; in osmosis, water diffuses down a water potential gradient.
Animal cells burst in pure water and shrink when placed in a concentrated solution. Plant cells do not burst in pure water because their cell wall stops this happening.
A plant cell in pure water takes up water by osmosis and becomes turgid, as its contents exert outward pressure on the cell wall. A plant cell in a concentrated solution loses water by osmosis. The cell becomes flaccid and may plasmolyse.
Active transport is the movement of particles across a cell membrane, up the concentration gradient, using energy from respiration.
Protein carriers in cell membranes change shape to move substances across the cell membrane during active transport.

PRACTICE QUESTIONS

1 **Identify** which change would increase the rate at which a substance diffuses across a membrane.

A a decrease in concentration gradient

B a decrease in the surface area of the membrane

C an increase in distance across the membrane

D an increase in temperature **[1]**

2 The table shows information about diffusion, osmosis and active transport. Identify which row is correct. **[1]**

	Diffusion	Osmosis	Active transport
A	uses energy from respiration	always involves a partially permeable membrane	uses protein carriers in membranes
B	uses kinetic energy of molecules and ions	uses kinetic energy of water molecules	involves movement up a concentration gradient
C	uses protein carriers in membranes	involves movement up a concentration gradient	always involves a partially permeable membrane
D	always involves a partially permeable membrane	uses protein carriers in membranes	uses energy from respiration

COMMAND WORD

identify: name/select/recognise.

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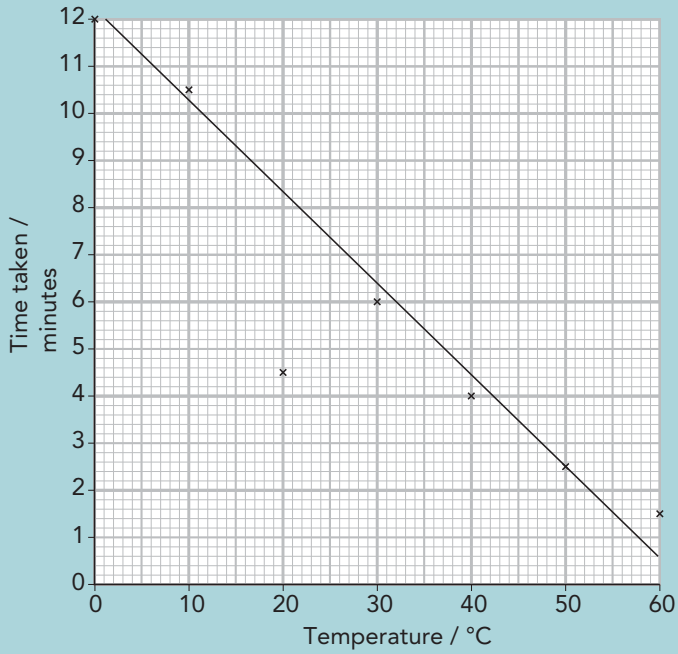
CONTINUED

3 A learner investigated how temperature affected the rate at which a dye moved through a piece of agar jelly.

She filled seven test-tubes with a solution of red dye. She placed each tube into a water-bath at a different temperature and left them for ten minutes.

She cut seven cubes of jelly. She placed each cube into one of the tubes containing the red dye. She measured the time taken for the cubes to change colour.

This graph shows her results.



a **Give** the name of the process by which the dye moved through the jelly, and **describe** this process.. **[3]**

b **Suggest** why the learner left the tubes of red dye in the water-baths for ten minutes. **[1]**

c **State** *two* variables that the learner should standardise (keep the same) in her experiment. **[2]**

d **i** One of the learner's results is anomalous (inconsistent). Identify this result and **explain** why you have chosen this value. **[2]**

ii Describe the trend or pattern shown by the results. **[1]**

iii Use your knowledge of diffusion to explain the results. **[2]**

[Total: 11]

4 **a** Describe what is meant by *osmosis*. **[2]**

b **Compare** the effect of immersing an animal cell and a plant cell in pure water. Explain the reasons for any differences that you describe. **[6]**

[Total: 8]

COMMAND WORDS

give: produce an answer from a given source or recall/memory.

describe: state the points of a topic/give characteristics and main features.

suggest: apply knowledge and understanding to situations where there is a range of valid responses in order to make proposals/put forward considerations.

state: express in clear terms.

explain: set out purposes or reasons/make the relationships between things clear/say why and/or how and support with relevant evidence.

compare: identify/comment on similarities and/or differences.

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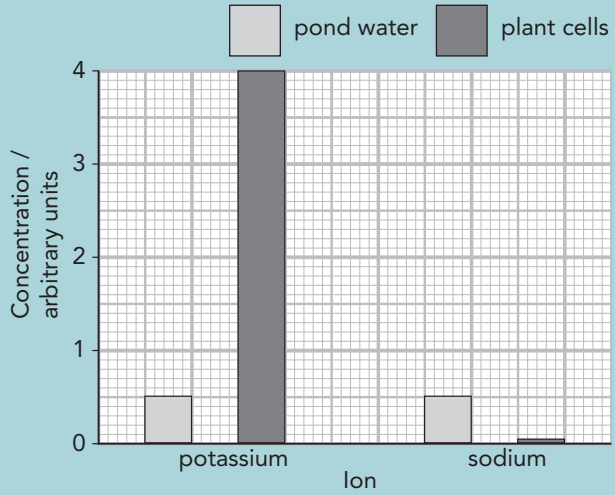
CONTINUED

5 This bar chart shows the concentration of potassium ions and sodium ions in a sample of pond water, and in the cells of a plant growing in the water.



a Describe the differences between the concentrations of the ions in the pond water and in the plant cells. **[3]**

b Use the data in the graph to suggest how the ions move between the pond water and the plant cells. Explain your answer. **[2]**

c Describe how the process you have described in your answer to b takes place. **[4]**

[Total: 9]

SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
explain what is meant by a diffusion gradient	B2.01			
describe how to investigate factors that affect diffusion	B2.01			
describe osmosis, referring to diffusion of water through a partially permeable membrane	B2.02			
describe osmosis, using the term water potential	B2.02			
describe and explain what happens when animal or plant cells are immersed in solutions of different concentrations	B2.02			
describe active transport	B2.03			
explain how active transport happens, including the role of protein carriers in membranes.	B2.03			

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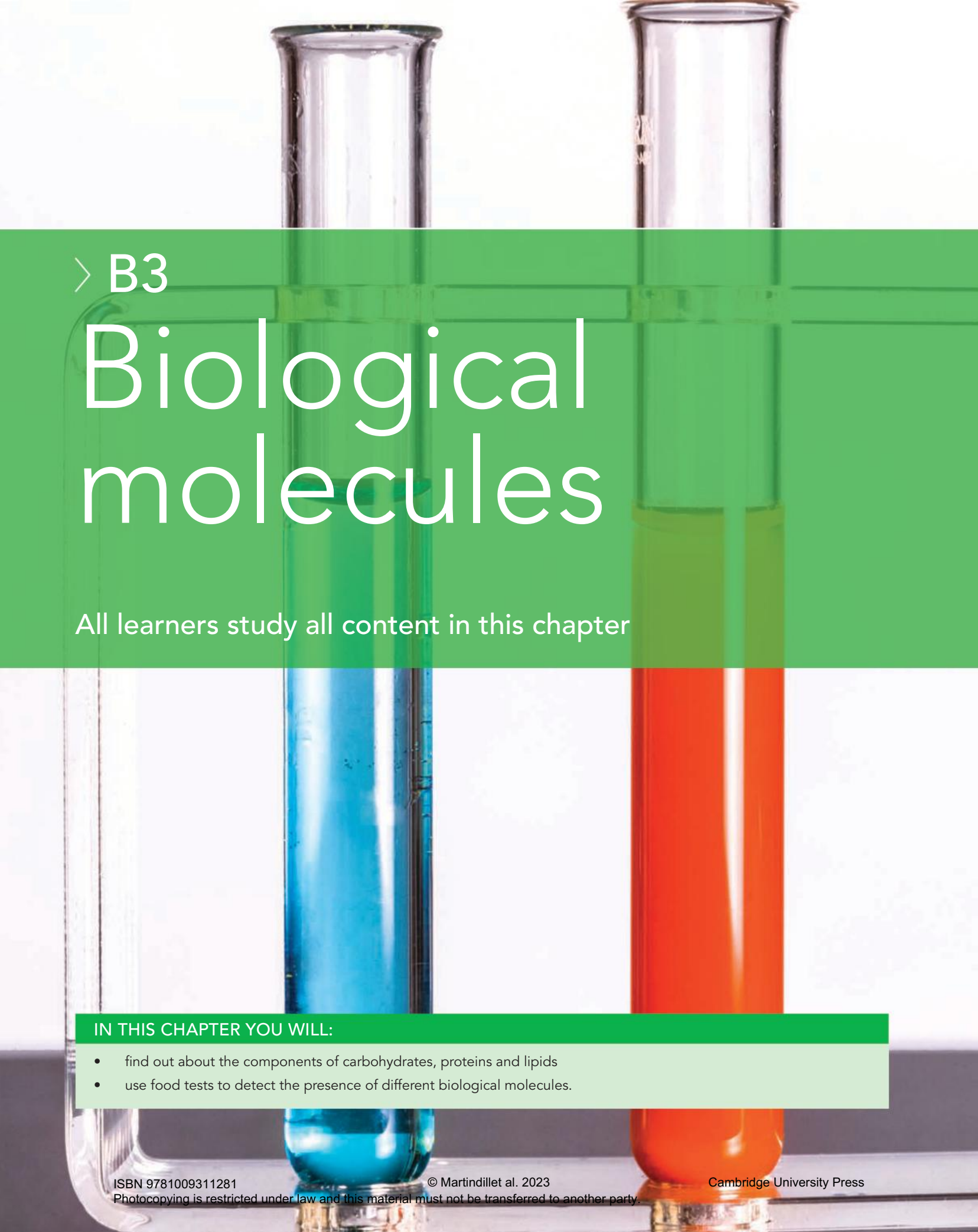

B3 Biological molecules

All learners study all content in this chapter

IN THIS CHAPTER YOU WILL:

- find out about the components of carbohydrates, proteins and lipids
- use food tests to detect the presence of different biological molecules.

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BEFORE YOU START

Work with a partner.

Can you answer these questions about elements, compounds, atoms and molecules?

1 Oxygen gas is made up of pairs of oxygen atoms combined together.
   - **a** What is the formula for oxygen gas?
   - **b** What do we call a particle made up of two or more atoms combined together?
   - **c** Is oxygen an element or a compound?

2 Glucose is made up of the elements that have the symbols C, H and O.
   - **a** What do C, H and O stand for?
   - **b** One molecule of glucose contains 6 atoms of carbon, 12 atoms of hydrogen and 6 atoms of oxygen. Can you write the formula for glucose?
   - **c** Is glucose an element, a compound or a mixture?

SCIENCE IN CONTEXT B3.01

How did life on Earth start?

One of the greatest mysteries of life on Earth is how it began.

Living cells are made up of biological molecules. These are not often found in non-living things. Scientists think that these molecules may have formed from simpler substances when the Earth was still very young, perhaps 4 billion years ago. The mixture of chemicals that we know existed in the seas and atmosphere at that time, and the energy provided by volcanic eruptions and lightning strikes, could possibly explain how these molecules of life were first produced.

Another possibility is that at least some of these molecules arrived on Earth from outer space.

Meteorites are rocks that arrive on Earth from space. Did molecules such as amino acids, the building blocks of proteins, delivered to Earth from space, perhaps contribute to the origin of life?

If we can understand how life first arose on Earth from biological molecules, this can help us to answer another important question: is there life anywhere else in the universe?

Discussion question

1 Most scientists think that all life on Earth today comes from other life. Suggest why scientists think it is unlikely that life could arise from non-living things today.

B3.01 Carbohydrates, fats and proteins

What is a human made of? The most abundant compound in our bodies is water, which makes up around 62% of our total body mass. About 16% is protein, another 16% is fat, and around 1% is carbohydrate. The remaining 5% is calcium and phosphorus (mostly in bones) and some other elements such as potassium, sodium, phosphate and chloride ions.

In this chapter, you will find out about the three main types of organic compounds that make up the bodies of all living things: carbohydrates, fats and proteins.

Carbohydrates

Carbohydrates include starch, cellulose and sugar. Carbohydrate molecules are made from three elements: carbon, hydrogen and oxygen. One molecule of carbohydrate contains about twice as many hydrogen atoms as carbon or oxygen atoms.

KEY WORD

carbohydrates: substances that include sugars, starch and cellulose; they contain carbon, hydrogen and oxygen.

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The simplest types of carbohydrate, with the smallest molecules, are **sugars**. Sugars taste sweet. They are soluble in water.

One type of sugar is **glucose**. A glucose molecule is made of 6 carbon atoms, 12 hydrogen atoms and 6 oxygen atoms. Its formula is $C_6H_{12}O_6$. These atoms are arranged to form a hexagon shape (Figure B3.01).

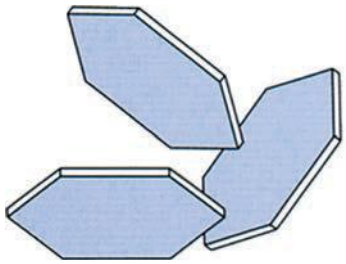

Figure B3.01: Glucose molecules are quite small and have a hexagon shape.

Glucose is the form in which carbohydrates are transported around the human body. Glucose dissolves in blood plasma, which delivers it to every cell. Cells need glucose for energy.

Glucose molecules can link together in chains, to form much larger molecules. In animals, the large molecules that are formed are **glycogen**. The liver helps to keep the concentration of glucose in the blood constant (you can read about this in Chapter B9).

In plants, glucose molecules are linked together in a slightly different way, to make **starch** (Figure B3.02). Starch is stored in plant cells. It can be broken down to form glucose again when the plant needs it.

You can detect the presence of starch using **iodine solution**. This changes from brown to blue–black if starch is present (Figure B3.03).

KEY WORDS

sugars: carbohydrates that have relatively small molecules; they are soluble in water and they taste sweet.

glucose: a sugar that is used in respiration to release energy.

glycogen: a carbohydrate that is used as an energy store in animal cells.

starch: a carbohydrate that is used as an energy store in plant cells.

iodine solution: a solution of iodine in potassium iodide; it is orange–brown, and turns blue–black when mixed with starch.

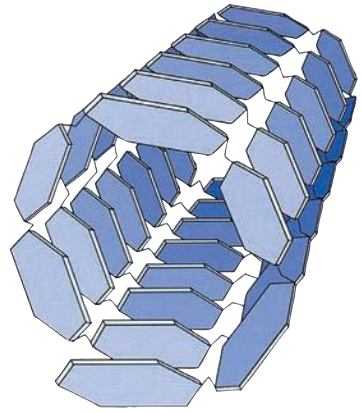

Figure B3.02: This represents a small part of a starch molecule. It is made from many glucose molecules linked together in a long chain, which coils into a spiral shape.

Figure B3.03: The blue–black colour shows that starch is present in the potato.

Most sugars can be detected using **Benedict's solution**. Benedict's solution is blue, and it changes colour when it is heated with **reducing sugars** such as glucose. The colour change is dependent upon the concentration of reducing sugar. The blue solution becomes green if very low concentrations of reducing sugar are present, yellow at slightly higher concentrations, and orange-red with very high concentrations. However, even low concentrations of glucose will eventually turn the blue colour to orange-red if heated for long enough (Figure B3.04).

KEY WORDS

Benedict's solution: a blue liquid that turns orange-red when heated with a reducing sugar.

reducing sugar: a sugar, such as glucose, which turns Benedict's solution orange-red when they are heated together.

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Figure B3.04: Positive results of the Benedict's test. The tube on the left contains a small amount of reducing sugar and the blue Benedict's solution has changed to green. The tube on the right contains a large amount of reducing sugar.

EXPERIMENTAL SKILLS B3.01

Testing for carbohydrates

You are going to test several different foods to find out if they contain starch or sugar.

You will need:

- a selection of foods to test, kept separate from one another
- a knife to cut the foods into small pieces
- a white tile
- a small bottle of iodine solution, with a dropper
- a water-bath set at about 80 °C (you can use an electric one or you can make your own water-bath by heating water in a beaker over a burner – see Figure B3.05)
- a thermometer to check the temperature of the water-bath (see note)
- several large test-tubes (boiling tubes), and a beaker to stand them in
- some Benedict's solution, with a dropper.

CONTINUED: B3.01

Note about water-baths: You may be able to use electric water-baths, which can be set to temperatures above room temperature. If you do not have these, you can make your own water-bath by heating water in a beaker over a burner (Figure B3.05). You can also make a water-bath with a temperature of 0 °C by filling a beaker with crushed ice. In this case, you can monitor the temperature of the water with a thermometer, and either heat with a burner or add cold water to try to keep the temperature fairly constant.

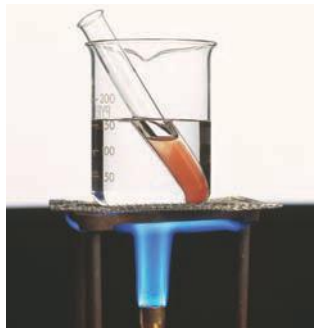

Figure B3.05: Heating a mixture of Benedict's solution and food in a water-bath, to test for reducing sugar.

Safety

Take care when using a knife to cut food.

Method: Testing for starch

1. Read through the instructions, and decide which foods you are going to test for starch.
2. Construct a results chart ready to fill in as you work. You will need a column for the food, another column for your observations, and a third column for your conclusion.

   When you record your results, make sure that you write down the colour that you see. Do not write 'no change'.
3. Take a small piece of the first food and place it on the white tile. Add a drop or two of iodine solution. If the iodine solution stays brown, there is no starch in the food. If you see a dark blue or black colour, then starch is present.
4. Repeat with several other samples of different foods.

Method: Testing for reducing sugars

1. Read through the instructions and construct a results chart.
2. Take some of your first food and cut it into very small pieces. Put the pieces into a boiling tube and add a little water. Shake the tube to try to dissolve any sugar in the food.

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CONTINUED: B3.01

3 Add enough Benedict's solution to cover the food. Shake the tube to mix the contents.

4 If you are using an electric water-bath, take a beaker and fill it with water from the water-bath. Stand the beaker in the water-bath. Stand the test-tube in the beaker.

If you have made your own water-bath, simply stand the test-tube in the beaker of hot water (Figure B3.05).

5 Watch as the mixture of food and Benedict's solution heats up. If it stays blue, there is no reducing sugar in the food. If it changes to red, there is reducing sugar in the food.

6 Repeat with several other samples of different foods.

Questions

1 Make a list of the foods that contained starch, and the foods that contained reducing sugar.

2 Do these foods come from plants, or from animals?

ACTIVITY B3.01

Comparing reducing sugar content

Work in a group of two or three for this activity.

When you tested foods for reducing sugar, you probably noticed that the red colour took a few minutes to appear.

The less time it takes for the red colour to appear, the more reducing sugar there is in the food.

Discuss how you could use this fact to compare the quantity of reducing sugar in three different foods. Write a list of instructions that someone could follow that would make it easy for them to make this comparison.

Peer assessment

When your group has completed the instructions, exchange the instructions with another group.

How well have they written their instructions? Would they be easy to follow? Would they give a correct indication of which food contained the most reducing sugar?

Give feedback to the group about what they have done well, and also one or two things that could be improved.

When you get your own feedback, think about it carefully. If you were asked to plan a similar experiment in future, what would you do differently?

Question

B3.01 Name *one* carbohydrate that is found in both plants and animals.

Fats and oils

Fats and **oils** are also known as **lipids**. A fat is a lipid that is solid at room temperature, and an oil is a lipid that is liquid at room temperature.

Fats and oils contain the three elements carbon, hydrogen and oxygen. You may remember that carbohydrates also contain these elements. However, in fats, each molecule contains much less oxygen than is found in a carbohydrate molecule.

Fat molecules are made of two kinds of smaller molecule: glycerol and fatty acids. Figure B3.06 shows how these are joined together to make a fat molecule.

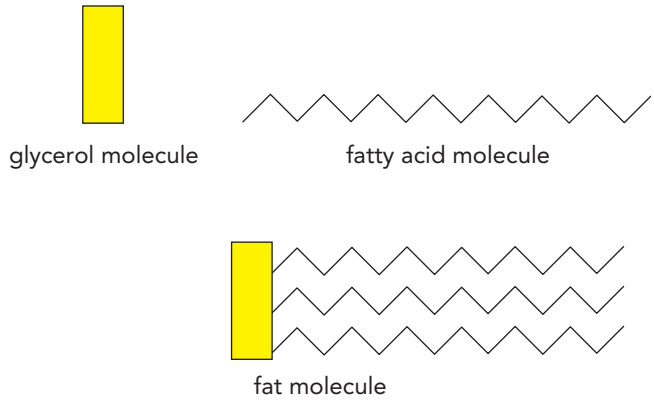

Figure B3.06: A fat molecule is made from a glycerol molecule and three fatty acid molecules combined together.

Fats are important for making cell membranes. They are also used as energy stores. Mammals often have a layer of cells containing fat droplets beneath the skin. This fat-containing tissue is both an energy store and a heat insulating layer.

KEY WORDS

fats: lipids that are solid at room temperature.

oils: lipids that are liquid at room temperature.

lipids: substances containing carbon, hydrogen and oxygen; they are insoluble in water and are used as energy stores in organisms.

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Fats and oils do not dissolve in water. However, they do dissolve in ethanol. We can use this to detect their presence in food. First, the food is cut into small pieces and shaken with ethanol. Any fats in the food will dissolve in the ethanol. Next, the ethanol is poured into a clean tube containing water. If there are fats in the ethanol, they form tiny droplets in the water, which give it a milky appearance (Figure B3.07). The mixture of tiny droplets in water is called an **emulsion**, so this test is called the ethanol emulsion test.

Figure B3.07: This milky appearance is what you see when you get a positive result using the ethanol emulsion test for fats and oils.

KEY WORD

emulsion: a liquid containing two substances that do not fully mix; one of them forms tiny droplets dispersed throughout the other.

Questions

B3.02 Animals that live in very cold places often have especially thick layers of fat underneath the skin (Figure B3.08). Suggest why.

B3.03 Fat stores contain more energy per gram than carbohydrate stores. Suggest why birds that are about to go on long migrations build up stores of fat before they fly.

Figure B3.08: Bearded seals have a really thick layer of fat underneath their skin.

EXPERIMENTAL SKILLS B3.02

Testing for fats and oils

You are going to test a selection of different foods to find out if they contain fats or oils.

You will need:

- a selection of foods to test, kept separate from one another
- a knife to cut the foods into small pieces
- several very clean test-tubes
- a small bottle of ethanol, with a dropper
- some distilled water.

Method

1. Read through the instructions and construct a results chart.
2. Take some of your first food and cut it into very small pieces. Put the pieces into a very clean test-tube and add a little ethanol. Shake the tube to try to dissolve any fats or oils in the food.
3. Take another clean test-tube and put some distilled water into it. Very carefully, pour the ethanol from the first tube into the distilled water. Do not let any of the food go in!

   If you see a milky white colour appearing, this shows that there was fat in the food.

Questions

1. Which food(s) gave a positive result? Which gave a negative result?
2. Use your observations to suggest how you could estimate which of the types of food contains the most fats and/or oils?

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Proteins

Protein molecules contain four elements: carbon, hydrogen, oxygen and nitrogen. Some proteins, but not all, also contain a small quantity of the element sulfur.

A protein molecule is made of a long chain of smaller molecules, called **amino acids** (Figure B3.09). There are 20 different amino acids. Each kind of protein has different amino acids linked together in a precise order. If even one amino acid is changed, or moves into a different place in the protein molecule, then we get a different protein. So, there is an almost infinite number of different kinds of protein that can be made.

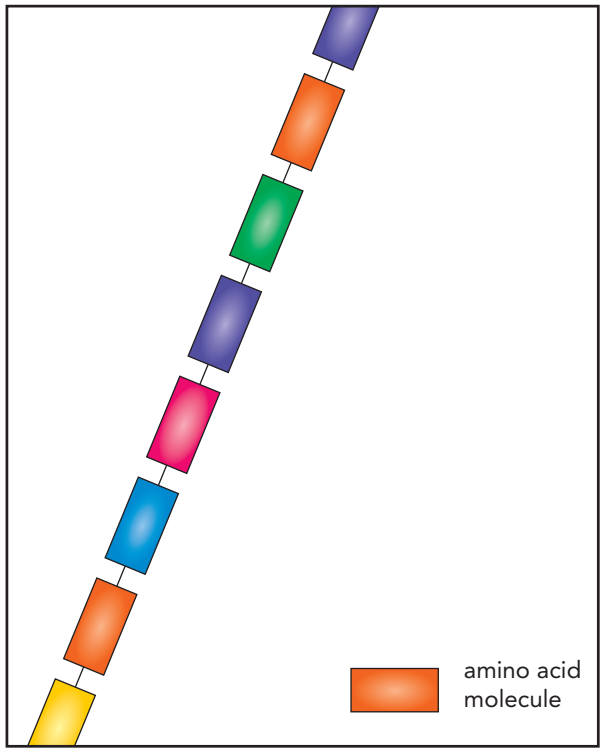

Figure B3.09: A small part of a protein molecule. Proteins are made of long chains of amino acid molecules.

Proteins have many different functions in organisms. All enzymes are proteins. (You will study enzymes in the next chapter.) **Antibodies**, which help to protect the body against **pathogens**, are proteins. So is haemoglobin, the red pigment that transports oxygen in mammalian blood. Proteins are also important for forming cell membranes in all organisms. In humans, hair and fingernails are made from a protein called **keratin**.

To test for proteins, we use **biuret reagent**. This is blue, and it changes to violet (purple) when in contact with proteins (Figure B3.10).

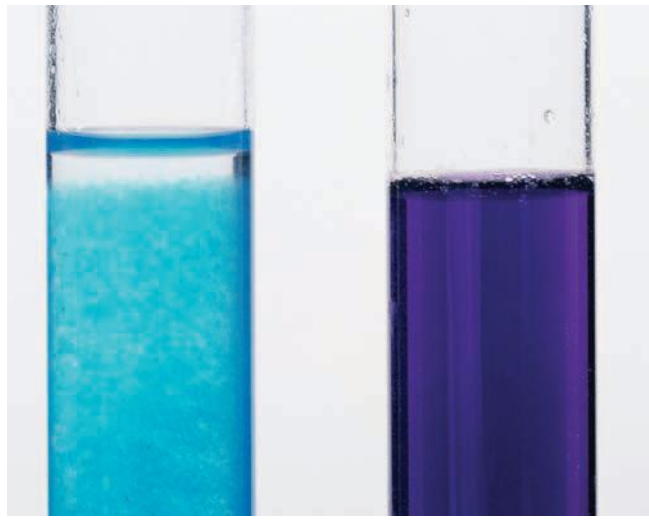

Figure B3.10: These are negative and positive results of the biuret test. The tube on the left has no protein, but the one on the right does contain protein.

KEY WORDS

protein: a substance whose molecules are made of many amino acids linked together; each different protein has a different sequence of amino acids.

amino acids: substances with molecules containing carbon, hydrogen, oxygen and nitrogen; there are 20 different amino acids found in organisms.

antibodies: molecules secreted by white blood cells, which bind to pathogens and help to destroy them.

pathogens: microorganisms, such as bacteria, that cause disease.

keratin: the protein that forms hair.

biuret reagent: a blue solution that turns purple when mixed with amino acids or proteins.

Question

B3.04 Which element is found in all proteins, but not in carbohydrates and fats?

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EXPERIMENTAL SKILLS B3.03

Testing for proteins

You are going to test a selection of different foods to find out if they contain proteins.

You may find it helpful to start by testing something that you know contains protein, such as cooked egg white. Keep a tube showing a negative result (biuret reagent added to water, which will be blue) with the tube showing a positive result (violet) in a test-tube rack, so you can refer to these to decide whether you have a negative or positive result in each of your food tests.

You will need:

- a selection of foods to test, kept separate from one another
- a knife to cut the foods into small pieces
- several clean test-tubes
- a small bottle of biuret solution with a dropper.

Safety

Take care when using a knife to cut food.

Method

1. Read through the instructions and construct a results chart.
2. Take some of your first food and cut it into very small pieces. Put the pieces into a clean test-tube and add some biuret solution. Shake the test-tube to mix the contents.
3. Look for a colour change from blue to violet.

Questions

1. Do any of the foods you investigated contain no protein? How sure are you of this?
2. Suggest one way you could improve the method to make the comparisons of the food types more valid.

Reflection

With a partner, discuss good ways of remembering the different reagents used for the three tests you have met in this topic.

Which methods do you think are likely to work best for you?

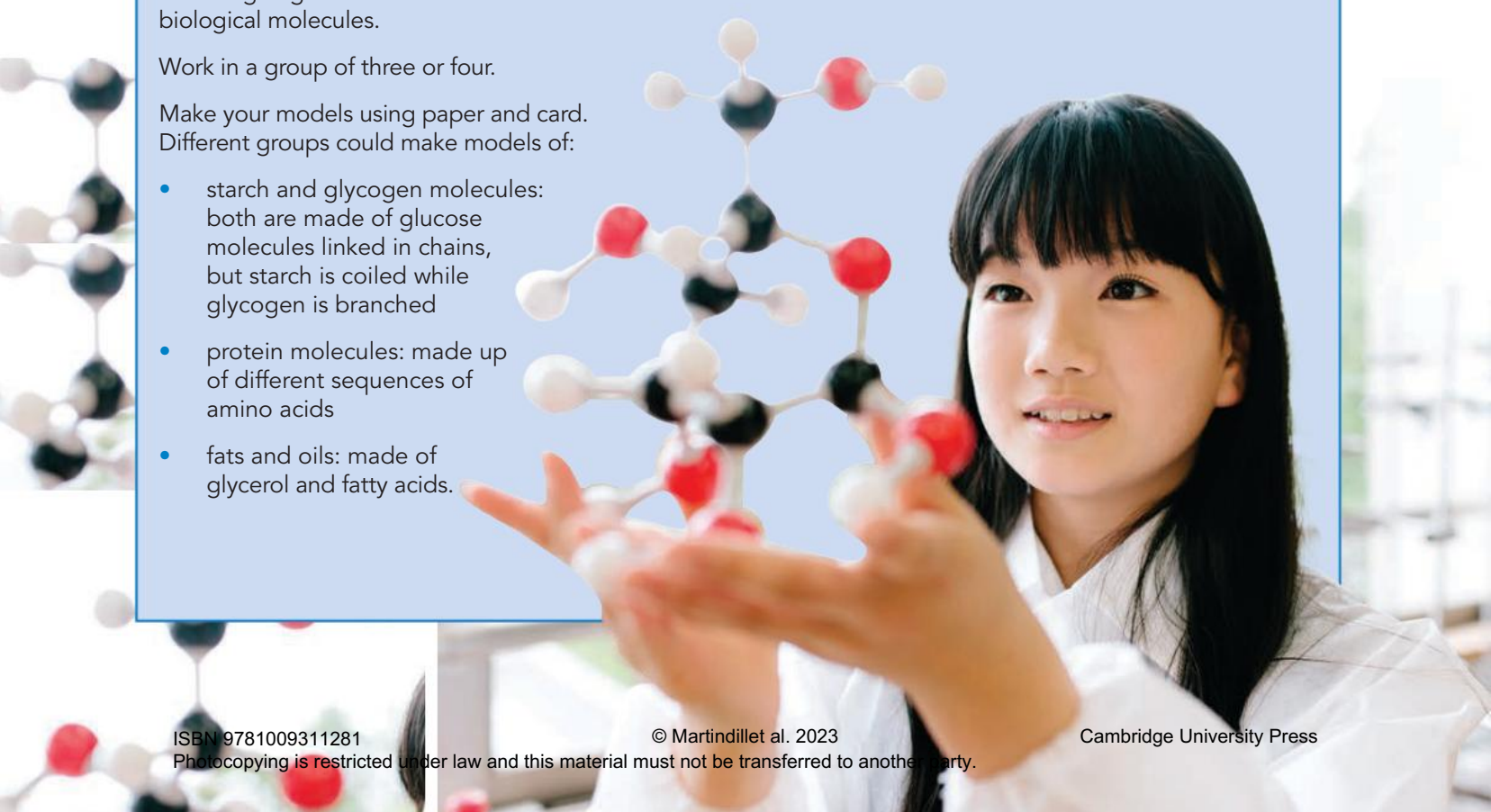
PROJECT B3.01 MODELLING BIOLOGICAL MOLECULES

You are going to make models of some biological molecules.

Work in a group of three or four.

Make your models using paper and card. Different groups could make models of:

- starch and glycogen molecules: both are made of glucose molecules linked in chains, but starch is coiled while glycogen is branched
- protein molecules: made up of different sequences of amino acids
- fats and oils: made of glycerol and fatty acids.



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SUMMARY

Carbohydrates are made of the elements C, H and O. Sugars, such as glucose, have relatively small molecules. Starch and glycogen are made of many glucose molecules linked in a long chain.
Starch can be detected using the iodine test. Benedict's solution is used to test for reducing sugars.
Fats and oils are also made of the elements C, H and O. Another name for fats and oils is lipids. A lipid molecule is made of three fatty acid molecules combined with one glycerol molecule.
The ethanol emulsion test is used to detect the presence of fats and oils.
Proteins contain the elements C, H, O and N. A protein molecule is made of many amino acid molecules combined in a long chain. There are 20 different amino acids, and their specific sequence in the molecule determines the specific protein that is formed.
Biuret reagent is used to test for proteins.

PRACTICE QUESTIONS

1 **Identify** which elements are contained in starch.

A carbon and hydrogen only

B carbon, hydrogen and oxygen

C carbon, hydrogen and nitrogen

D carbon, oxygen and nitrogen **[1]**

2 The table shows the results of tests on four samples of food.

Identify which food contains *only* fat. **[1]**

	Iodine test	Benedict's test	Ethanol emulsion test	Biuret test
A	brown	blue	milky white	blue
B	blue–black	red	colourless	purple
C	brown	blue	colourless	blue
D	blue–black	red	milky white	purple

3 Glucose, starch and glycogen are carbohydrates.

a Identify which substance(s) are found in plants only, and not in animals? **[1]**

b **Give** the elements that the molecules of all these substances contain. **[1]**

c **Describe** the structure of a starch molecule. **[2]**

d Glucose is a reducing sugar. Describe how you could test a liquid to find out if it contains glucose. **[3]**

[Total: 7]

COMMAND WORD

identify: name/select/recognise.

COMMAND WORDS

give: produce an answer from a given source or recall/memory.

describe: state the points of a topic/give characteristics and main features.

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CONTINUED

4 a Biuret reagent is used to test for proteins.

These statements about the biuret test are incorrect. Identify the errors so that you can write corrected versions of each statement.

i To carry out the biuret test, add biuret solution to the food and heat gently. **[1]**

ii If a food contains protein, biuret reagent turns from purple to blue. **[1]**

b Ethanol is used to test for fats and oils.

i Describe how you would carry out the ethanol test. **[3]**

ii Describe what you would see if the test gave a positive result. **[1]**

[Total: 6]

SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
list the chemical elements that make up carbohydrates, fats and proteins	B3.01			
state that starch and glycogen are made from glucose	B3.01			
state that fats and oils are made from fatty acids and glycerol	B3.01			
state that proteins are made from amino acids	B3.01			
describe how to use the Benedict's test for reducing sugars	B3.01			
describe how to use the iodine test for starch	B3.01			
describe how to use the biuret test for proteins	B3.01			
describe how to use the ethanol emulsion test for fats and oils.	B3.01			

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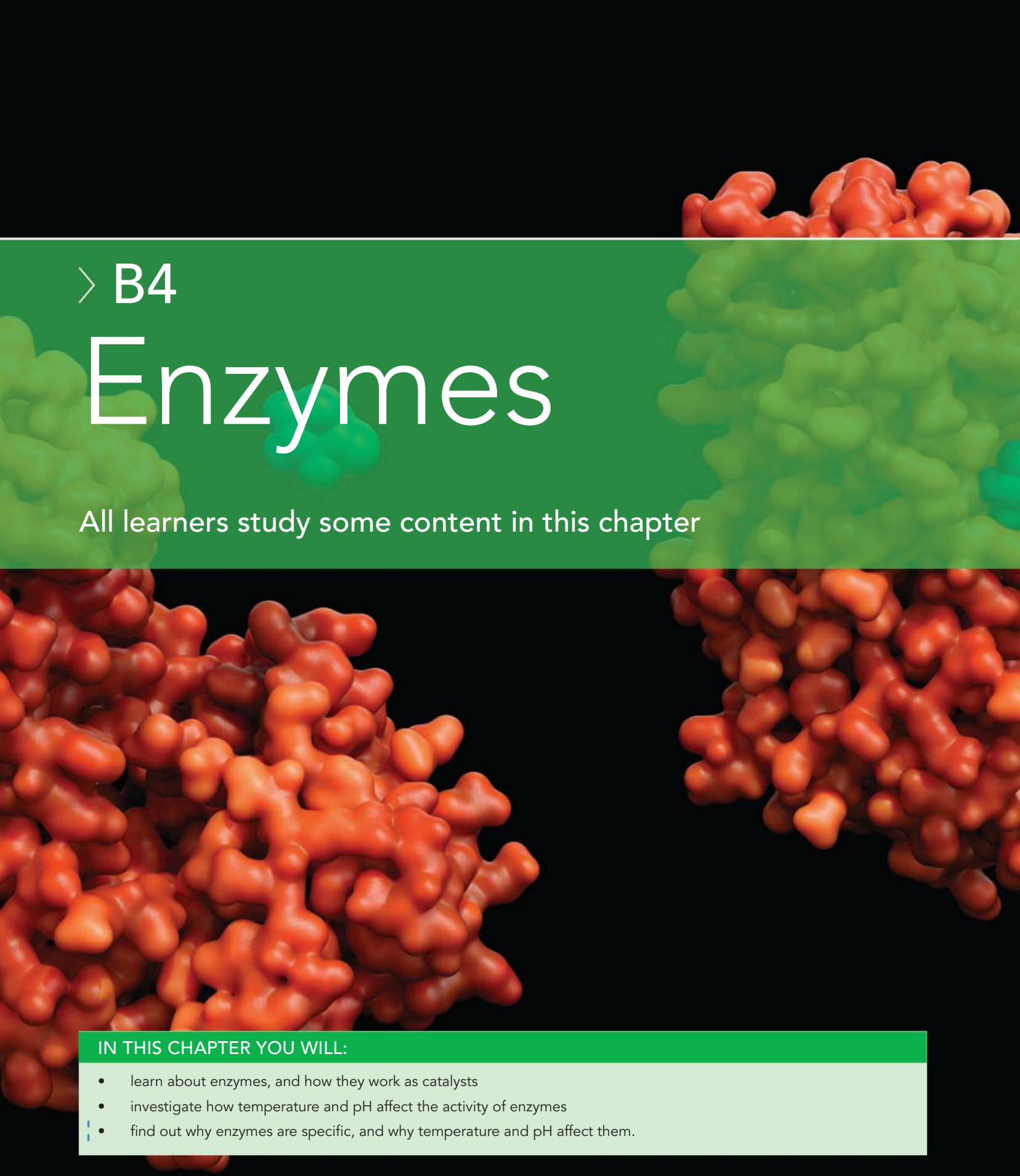

B4 Enzymes

All learners study some content in this chapter

IN THIS CHAPTER YOU WILL:

- learn about enzymes, and how they work as catalysts
- investigate how temperature and pH affect the activity of enzymes
- find out why enzymes are specific, and why temperature and pH affect them.

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BEFORE YOU START

Work with a partner.

Here are some statements about chemical reactions. Two of them are incorrect.

Can you identify these incorrect statements? When you think you have identified them, change them so that they are correct.

In a chemical reaction:

- one or more substances are changed to one or more new substances
- a large molecule may be split into smaller molecules
- atoms of one element are rearranged to make atoms of other elements
- small molecules may combine to form larger molecules
- products are changed to reactants.

SCIENCE IN CONTEXT B4.01

The dangers of dairy products

All mammals feed their young on milk (Figure B4.01). Milk is an excellent food. It contains carbohydrates, fats, proteins, minerals and vitamins.

Figure B4.01: Young guanacos feed on milk from their mother, just like all young mammals.

Humans are mammals, so therefore human babies feed on milk. To help babies digest the carbohydrates in milk, they produce an enzyme called lactase. This enzyme breaks a sugar called lactose into smaller molecules. These smaller molecules can then be absorbed into the blood.

Most people stop making lactase once they are old enough to take in food other than milk. But some people continue to make lactase all their lives. They can drink milk and eat dairy products (foods made from milk), with no problems. For everyone else, though, eating these foods makes them feel ill. They are intolerant to lactose, because they do not make lactase. The lactose is not broken down in their digestive system. It stays inside the alimentary canal (the tube that food passes through). This makes water move into the canal by osmosis. All this extra water in the alimentary canal can cause diarrhoea. Also, the lactose provides food for the bacteria that live in the alimentary canal. As the bacteria feed on the lactose, they produce gases as a waste product. This can cause abdominal pain and flatulence.

What is the solution to lactose intolerance? The simplest solution is not to eat foods containing lactose. Another approach is to take pills that contain the enzyme lactase. If a lactose-intolerant person swallows one of these pills before eating dairy products, they may avoid these unpleasant symptoms.

Discussion question

1 If most people stop making lactase when they are adults, there must be some advantage in this. Discuss what this might be.

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B4.01 Biological catalysts

Many chemical reactions can be sped up by substances called catalysts. A **catalyst** alters the rate of a chemical reaction, without being changed itself.

Within any living organism, chemical reactions are taking place all the time. These reactions are called metabolic reactions. Almost every metabolic reaction is controlled by catalysts called **enzymes**. Without enzymes, the reactions would take place very slowly or not at all. Enzymes ensure that the rates of metabolic reactions are fast enough to sustain life.

For example, inside the intestines, large molecules are broken down to smaller ones in the process of digestion. These reactions are speeded up by enzymes. A different enzyme is needed for each kind of nutrient. For example, starch is digested to a sugar called maltose by an enzyme called **amylase**. Proteins are digested to amino acids by **protease**.

These enzymes are also found in plants. For example, in germinating seeds enzymes digest the food stores (mainly starch) for the growing seedling.

Another enzyme which speeds up the breakdown of a substance is **catalase**. Catalase works inside all the cells of living organisms. It breaks down hydrogen peroxide to water and oxygen. This is necessary because hydrogen peroxide is produced by many of the chemical reactions which take place inside cells. Hydrogen peroxide is a very dangerous substance and must be broken down immediately.

$$\text{hydrogen peroxide} \xrightarrow{\textit{catalase}} \text{water + oxygen}$$

Not all enzymes help to break things down. Many enzymes help to make large molecules from small ones. For example, enzymes help to link amino acids together to make proteins inside cells.

KEY WORDS

catalyst: a substance that increases the rate of a chemical reaction and is not changed by the reaction.

enzymes: proteins that are involved in all metabolic reactions, where they function as biological catalysts.

amylase: an enzyme that catalyses the breakdown of starch to maltose.

protease: an enzyme that catalyses the breakdown of protein to amino acids.

catalase: an enzyme that catalyses the breakdown of hydrogen peroxide to water and oxygen.

Naming enzymes

Enzymes are named according to the reaction that they catalyse. Their names often end in -ase. For example, enzymes that catalyse the breakdown of carbohydrates are called **carbohydrases**. If they break down proteins, they are proteases. If they break down fats and oils (lipids) they are **lipases**.

Sometimes, enzymes are given more specific names than this. For example, we have seen that the carbohydrase that breaks down starch is called amylase. A carbohydrase that breaks down maltose is called **maltase**. A carbohydrase that breaks down sucrose is called **sucrase**.

The substance that an enzyme changes is called its **substrate**. The substrate of amylase is starch. The substrate of lipase is lipids.

Notice how careful you have to be to spell the name of the enzyme and its substrate correctly, and to write clearly. *Maltose* and *maltase* can look almost the same if you do not write carefully.

KEY WORDS

carbohydrases: enzymes that break down carbohydrates.

lipases: enzymes that break down lipids (fats and oils).

maltase: an enzyme that catalyses the breakdown of maltose to glucose.

sucrase: an enzyme that breaks down sucrose.

substrate: the substance that an enzyme causes to react.

Questions

B4.01 Explain why enzymes are called *biological catalysts*.

B4.02 You read about the enzyme lactase at the start of this chapter.

a What type of enzyme is lactase?

b Name the substrate of lactase.

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How enzymes work

Each type of enzyme has molecules with a very specific shape. The enzyme molecule has a 'dent' in it, called the **active site** (Figure B4.02).

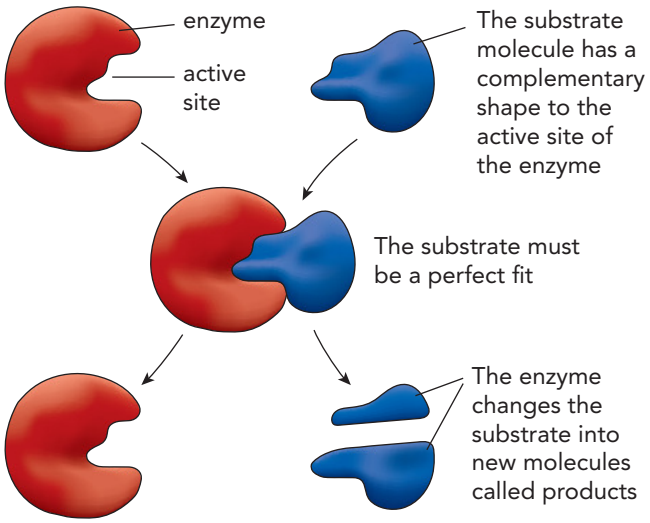

Figure B4.02: How an enzyme catalyses a reaction.

An enzyme works by allowing a molecule of its substrate to fit into the active site, where the substrate and the enzyme bind together. For this to happen, the fit has to be perfect. We say that the shape of the enzyme and the shape of the substrate are **complementary** to one another.

When the substrate is in the active site and bound to the enzyme, the enzyme changes the substrate into a new substance called the **product**. Then the product breaks away from the enzyme. Now the enzyme is free, and ready to bind with another substrate molecule.

In Figure B4.02, the substrate is a single molecule, and it is broken into two product molecules. Enzymes can also catalyse reactions where two substrate molecules bind with its active site and are joined together to form a single product molecule.

KEY WORDS

active site: the part of an enzyme molecule to which the substrate temporarily binds.

complementary: with a perfect mirror-image shape.

product: the new substance formed by a chemical reaction.

You have probably taken a few minutes to read about how enzymes work, and to look at the diagram in Figure B4.02. In that time, a single enzyme molecule could have catalysed millions of reactions. The enzyme catalase is the fastest enzyme known. One catalase molecule can break down an almost unbelievable 44 million hydrogen peroxide molecules in one second.

The short-lived structure that forms as the substrate slots into the enzyme's active site has its own name. It is called the **enzyme–substrate complex**.

ACTIVITY B4.01

Enzyme specificity

Each enzyme can only catalyse reactions with one type of substrate. This is described as enzyme **specificity**.

Take a minute or two to think about why enzymes are specific. Then discuss your ideas with a partner.

Be ready to share your ideas with the rest of the class.

KEY WORDS

enzyme–substrate complex: the short-lived structure formed as the substrate binds temporarily to the active site of an enzyme.

specificity: of enzymes, only able to act on a particular (specific) substrate.

B4.02 Factors that affect enzymes

We have seen that enzymes act very quickly. Each enzyme molecule can change many substrate molecules to products every second.

But there are some factors that can affect this speed of action. Enzymes are very sensitive to temperature and pH. Each kind of enzyme has a particular temperature and pH at which it works fastest (Figures B4.03a and b). These are called the **optimum** temperature, and the optimum pH, for that enzyme.

KEY WORD

optimum: best; for example, the optimum temperature of an enzyme is the temperature at which its activity is greatest.

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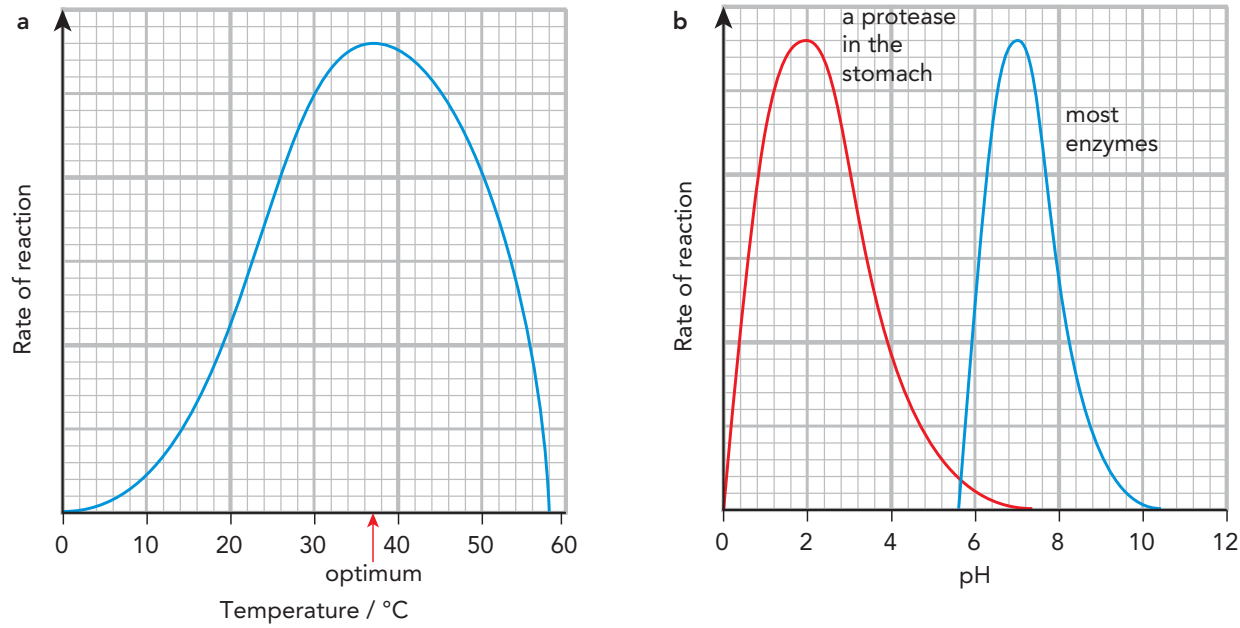

Figure B4.03 a: The effect of temperature on enzyme activity. **b:** The effect of pH on enzyme activity.

Questions

B4.03 Look at Figure B4.03a. Describe what is shown on the graph. (When you are describing a graph, it is a good idea to quote figures, with units.)

B4.04 Look at Figure B4.03b.

a What is the optimum pH of the protease in the stomach?

b What is the optimum pH of most enzymes?

c What is the **range** of pH values at which most enzymes are able to work?

KEY WORDS

range: the lowest to the highest value.

buffer solution: a liquid that has a known pH, and that keeps that pH steady all the time.

EXPERIMENTAL SKILLS B4.01

Investigating the effect of pH on the activity of catalase

You are going to find out how changing the pH affects the rate at which catalase breaks down hydrogen peroxide to water and oxygen.

You will change the pH using **buffer solutions**. A buffer solution is a liquid that has a particular pH. It keeps this pH the same, even if chemical reactions take place.

You will use catalase from celery or any other plant such as a potato, or some leaves. You can mash up the celery in water, so that the catalase forms a solution in the water. It is best if this is done once for the whole class.

You will need:

- a blender or liquidiser, or a pestle and mortar
- some fresh plant material, such as celery
- distilled water
- muslin or a sieve, and a filter funnel
- some 3% hydrogen peroxide solution
- five 50 cm^3 beakers
- small measuring cylinders or syringes, to measure 5 cm^3 and 10 cm^3
- five buffer solutions, each with a different pH
- 15 small squares of filter paper, all the same size (about 5 mm × 5 mm)
- forceps (tweezers)
- a stopwatch or timer.

Safety

Take care if you are using a blender or liquidiser.

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CONTINUED: B4.01

Before you start

Practise using the forceps to pick up the little pieces of filter paper. It is not easy!

Method

1 Cut up some celery and put it into a blender. Add water and blend. If you do not have a blender, cut the celery into small pieces and grind it with water using a pestle and mortar.

2 Pour the mixture of celery and water through some muslin, using a filter funnel, or through a sieve. (It takes too long if you use filter paper.) This will separate out most of the bits of celery from the liquid.

3 You now have a liquid containing catalase. Label a beaker 'catalase solution' and pour some of this liquid into it.

4 Copy the results table below.

pH	Time taken for paper to rise to top / s			
	1st try	2nd try	3rd try	Mean

5 Find out which buffer solutions you will be using. Write them into your results chart. Label each of the small beakers with the pH of one of the buffer solutions.

6 Measure 5 cm^3 of hydrogen peroxide solution into each labelled beaker.

7 Measure 10 cm^3 of the appropriate buffer solution into each beaker.

8 Use forceps to pick up one of the little squares of filter paper. Dip the paper into the liquid containing catalase (Figure B4.04).

9 Get your stopwatch ready. Still using the forceps, push the paper to the bottom of the hydrogen peroxide solution in one of the small beakers. Let it go, and time how long it takes for the paper to rise to the top of the liquid (Figure B4.05). Record this in your results table.

10 Repeat steps 8 and 9 twice more, using the hydrogen peroxide solution in the same small beaker.

11 Now repeat steps 8, 9 and 10 for the other small beakers.

12 Collect a sheet of graph paper. Draw a line graph to display your results. Put pH on the *x*-axis, and the mean time it took the paper to rise to the top on the *y*-axis. Join your points with ruled straight lines.

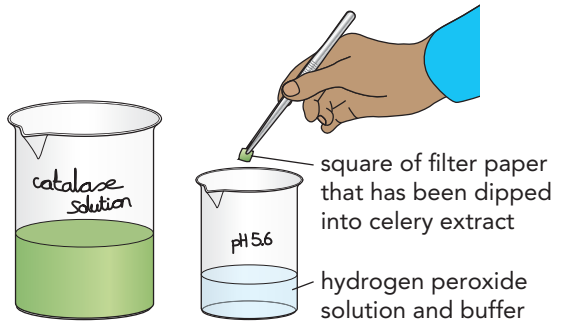

Figure B4.04: The filter paper has been soaked in the catalase solution, and is ready to put into the hydrogen peroxide solution.

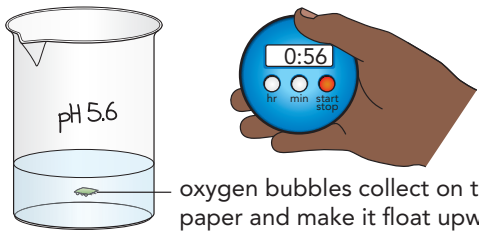

Figure B4.05: The catalase on the filter paper breaks down the hydrogen peroxide in the beaker, producing oxygen.

Questions

1 Write the word equation for the chemical reaction that took place in the small beakers.

2 Explain, in your own words, why the pieces of filter paper rose to the top of the liquid in the beaker.

3 Describe the relationship between the pH and the time taken for the filter paper to rise to the top of the liquid.

4 Did you have any anomalous results? If so, explain why you decided that these results were anomalous. Explain how you dealt with these results when you drew your graph.

5 Use your results to estimate the optimum pH of the catalase that you used.

6 Suggest what you could do to obtain a more precise value for the optimum pH of this enzyme.

7 Evaluate your experiment by identifying the main sources of error. Suggest how you could improve the experiment, to reduce these sources of error and give you more confidence that your results are correct.

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EXPERIMENTAL SKILLS B4.02

Investigating the effect of temperature on the activity of lipase

Lipase is an enzyme that catalyses the breakdown of lipids (fats and oils).

$$\text{lipid} \xrightarrow{\textit{lipase}} \text{fatty acids and glycerol}$$

Fatty acids are acids, so they decrease the pH. You will use an indicator called thymolphthalein to detect their presence. Thymolphthalein is blue in alkaline conditions and loses its colour when the pH becomes less alkaline.

You will need:

- fresh milk
- lipase solution, with a concentration of about 5%
- sodium carbonate solution, with a concentration of 0.05 mol dm^{-3}
- a small bottle of thymolphthalein indicator, with a dropper
- five test-tubes and a rack to stand them in
- a test-tube holder
- a syringe or measuring cylinder to measure 10 cm^3
- a small syringe to measure 1 cm^3
- a stopwatch or timer
- one or more glass rods
- water-baths at five different temperatures, ensuring that there are at least two below the optimum temperature for the enzyme, and two above (see note about water-baths in Chapter B3, and Figure B4.06 which shows an electric water-bath and a simple one made using a beaker over a burner)
- a thermometer
- a waterproof marker to label the test-tubes.

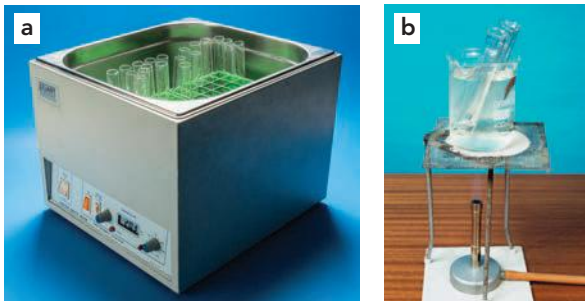

Figure B4.06 a: An electric water-bath, which you can set to a particular temperature. **b:** A water-bath over a burner.

Safety

Take care not to knock over the beaker of water if you have made your own water-bath. Stand up while you are working, so that if something does get knocked over you can quickly move out of the way.

If the water-bath is very hot, do not touch the hot water, or a hot test-tube, with your hands. Use a test-tube holder.

Reflection

The instructions for these experiments are quite long and complicated. How did you deal with that? What can you do in the future, to help you to understand complicated instructions and follow them successfully?

Method

1 Read through the instructions and draw a results chart that you can fill in as you work.

2 Label your test-tubes with your initials.

3 Measure 5 cm^3 of milk into each test-tube (Figure B4.07).

4 Measure 7 cm^3 of sodium carbonate solution into each test-tube.

5 Add five drops of thymolphthalein indicator to each test-tube. This will make the liquid go blue. Stir the contents using the glass rod.

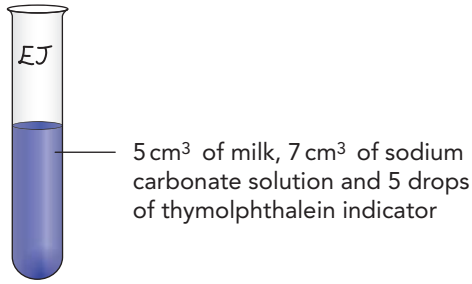

Figure B4.07: One of the tubes, ready to go into the water-bath.

6 Stand each test-tube in a water-bath at a different temperature. Leave the test-tubes for a few minutes, so that the contents come to the same temperature as the water-bath. Measure this temperature and record it.

7 Using the small syringe, add 1 cm^3 of lipase to the first test-tube. Start timing immediately. Stir with a clean glass rod, to mix the lipase into the milk.

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CONTINUED: B4.02

8 Record the time taken for the blue colour to disappear. Measure the time to the nearest second.

9 Repeat for the other four temperatures.

10 Use your results to draw a line graph. Put temperature on the *x*-axis and time taken on the *y*-axis. Join the points with ruled lines between them.

Questions

1 Explain why the liquid containing the milk was blue at the start of the experiment.

2 Explain why the liquid in some of the tubes became colourless.

3 Describe how temperature affected the time taken for the liquid to become colourless.

4 According to your results, what is the optimum temperature for lipase?

5 Your timer probably measured to 0.1 or even 0.01 seconds. Suggest why it is sensible to record the times to the nearest second.

6 Evaluate your experiment, by identifying the main sources of error. How could you improve the experiment, so that you have more confidence in your results?

Self assessment

How well did you construct and complete your results chart? Rate yourself for each of the following statements using:

☺ if you did it really well

😐 if you made a good attempt at it and partly succeeded

☹ if you did not try to do it, or did not succeed.

- I drew the results chart using a ruler for all the rows and columns.
- I included the units (s for the time measurements, and °C for the temperature measurements) in the headings of the table.
- I did not write the units again with the individual results in the table.
- I recorded each temperature reading to the nearest whole degree or 0.5 degree.
- I recorded each time reading to the nearest second.
- A friend confirms that my results chart is very easy to understand.

Denaturation

We have seen that enzymes have an optimum temperature, at which they work fastest. Enzymes from the human body generally have an optimum temperature of about 37 °C. Enzymes from plants may have optimum temperatures much lower than this. Some bacteria, especially those that live in hot springs, may have really high optimum temperatures: up to 80 °C in some cases.

For many enzymes, a temperature above about 60 °C completely stops them working. This is because the high temperature damages the enzyme. The enzyme is said to be denatured. It cannot catalyse its reaction any more.

Enzymes also have an optimum pH. For most enzymes, this is around pH 7. However, there are some enzymes that work best in a much higher or lower pH than this. For example, in Chapter B6 you will find out about an enzyme that works best in the acidic conditions in the human stomach – at a pH of about 2.

When an enzyme is placed in a liquid with a pH that is not its optimum pH, it is damaged. The enzyme is denatured and cannot catalyse its reaction.

Explaining how temperature and pH affect enzyme activity

Look at the graph in Figure B4.03a. You can see that at 0 °C, the enzyme has no activity. At this temperature, molecules have very little kinetic energy. They are moving only slowly. As they are moving slowly, the substrate molecules rarely collide with the enzyme. So, they rarely enter its active site, and very few substrate molecules are converted to product.

As the temperature increases, the kinetic energy of the enzyme and substrate molecules increases. They move faster and collide with each other more frequently and with more energy. Effective collisions are more frequent. Each second, more substrate molecules collide with an active site and are converted to product. This is why the graph shows enzyme activity increasing as temperature increases.

However, if the temperature increases above the optimum, the kinetic energy of the enzyme begins to shake it apart. Its molecules begin to lose their shape, so that the active site is no longer a true complementary shape to the substrate. When a substrate molecule collides with an active site, it may not fit. It cannot form an enzyme–substrate complex and is not converted to product.

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The activity of the enzyme therefore decreases. When the temperature reaches 60 °C, the active site is so out of shape that the enzyme has completely stopped working. It is completely denatured.

Something similar happens when pH changes. Each enzyme molecule has a very specific shape, with the active site being the best fit for the substrate at its optimum pH. A pH well above or below this value causes the enzyme molecule to lose its shape (denature), so it can no longer bind with the substrate.

Questions

B4.05 Look at the graph that you drew from your results in Experimental skills B4.02 Investigating the effect of temperature on the activity of lipase. In your own words, explain the shape of the graph (use your biological knowledge and understanding to give reasons for the shape of the graph).

B4.06 Use your own words to explain the shapes of the curves for most enzymes, in Figure B4.03b.

PROJECT B4.01 AN ENZYME DEMONSTRATION

It is best to work in a group of three for this project.

You are going to use your knowledge of enzymes to produce a short demonstration to explain what enzymes are and how they work. Your demonstration could be 'live' with a commentary, or you could make a video with a voiceover.

Imagine that your audience do not know anything about enzymes. Your task is to get them interested in enzymes, and help them to begin to understand what enzymes are and what they do. Work with your group to plan what you will do.

Figure B4.08: Raw liver contains a lot of catalase, which breaks down hydrogen peroxide and releases oxygen very quickly.

The best enzyme to use in your demonstration is catalase, because it is easy to see it working (Figure B4.08). Catalase is present in all animal and plant tissues. When catalase breaks down hydrogen peroxide, it releases oxygen. If you use an animal tissue such as liver, the reaction can be quite dramatic.

Although this is fun, it might be better to use something that reacts a little more quietly, such as potato (Figure B4.09).

Figure B4.09: If hydrogen peroxide is added to raw potato, the catalase in the potato breaks it down and releases oxygen, which forms a white froth.

Safety

It is extremely important to consider safety as you plan. What are the risks that you need to be aware of? How will you reduce these risks?

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SUMMARY

Enzymes are proteins that function as biological catalysts and increase the rate of metabolic reactions.
Without enzymes, these reactions would not take place fast enough to sustain life.
Each enzyme has an active site that has a complementary shape to its substrate.
When the substrate binds with the active site of the enzyme, the substrate is converted to product. The enzyme is unchanged.
The binding of substrate to the active site of the enzyme forms an enzyme–substrate complex.
Enzymes have an optimum temperature and pH at which they work most quickly. Higher temperatures or a very different pH cause the enzyme to change shape and denature.
As temperature increases, the kinetic energy of enzyme and substrate molecules increases, and they collide more frequently. This increases the rate of activity of the enzyme. However, above the optimum temperature, the enzyme begins to lose its shape, until it can no longer combine with the substrate. The shape of the active site is no longer complementary to the shape of the substrate.

PRACTICE QUESTIONS

1 **Identify** the smaller molecules from which an enzyme molecule is made.

A amino acids
B fatty acids
C glucose
D glycerol **[1]**

2 **a** Complete the sentences about enzymes.
Choose words from the list.

chemical **proteins** **metabolic** **active** **complementary**

Enzymes are _____ that function as biological catalysts.

Enzymes are involved in all _____ reactions.
The part of an enzyme where a substrate binds is called its

_____ site. **[3]**

b **Describe** why enzymes are important to all living organisms. **[2]**

[Total: 5]

COMMAND WORD

identify: name/select/recognise.

COMMAND WORD

describe: state the points of a topic/give characteristics and main features.

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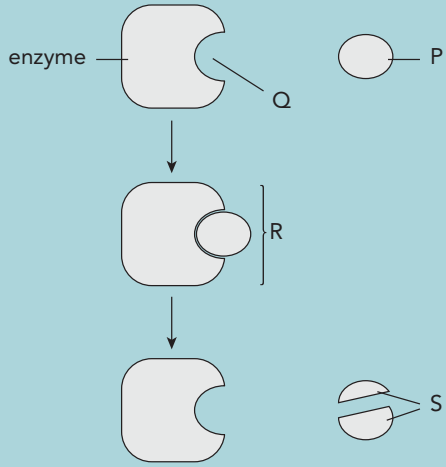
CONTINUED

3 The figure below shows some stages in an enzyme-controlled reaction.



Identify the parts labelled P, Q, R and S.

P: _____

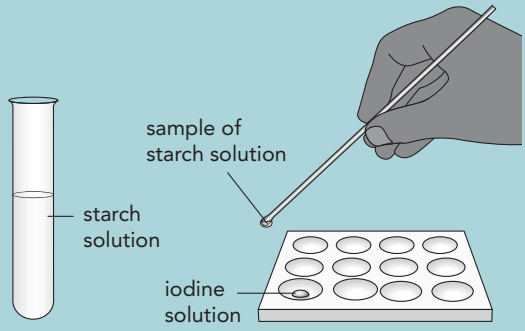
Q: _____

R: _____

S: _____ **[4]**

4 Amylase is an enzyme that breaks down starch to maltose.

a A student put some starch solution into a test-tube. He took a small sample of starch from the tube and added it to a drop of iodine solution on a white tile.



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Next, he added some amylase solution to the starch solution. After five minutes, he took another sample from the tube, and tested it with iodine solution.

The table shows his results.

	Result of iodine test
At start	blue–black
After adding amylase solution	brown

Explain the student's results. **[3]**

b The student investigated the effect of pH on the activity of amylase.

He placed the same volume of starch solution in five tubes. He added different buffer solutions to each tube. He then added amylase solution to each tube.

He took samples of the mixture from each tube and measured the time for all the starch to disappear.

His results are shown in the table.

pH	Time for starch to disappear / min
4	did not disappear
6	8
7	4
9	14
11	did not disappear

i Use the student's results to describe the effect of pH on the activity of amylase. **[3]**

ii The student kept the volume of starch solution the same in each tube.

State *three* other variables that the student should have kept the same in his experiment. **[3]**

[Total: 9]

COMMAND WORD

explain: set out purposes or reasons/make the relationships between things clear/say why and/or how and support with relevant evidence.

COMMAND WORD

state: express in clear terms.

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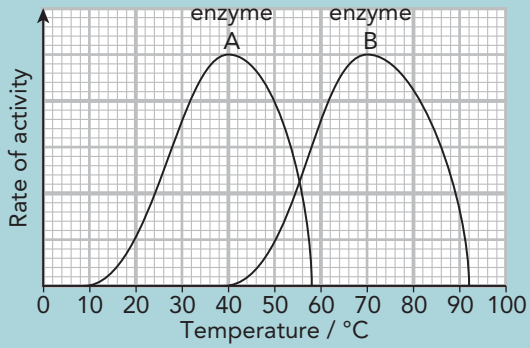
CONTINUED

5 The graph below shows how the activity of two enzymes, A and B, is affected by temperature.



a Compare the effect of temperature on enzyme **A** and enzyme **B**. **[5]**

b Explain the effect of temperature on enzyme B from:

i 40 to 60 °C **[3]**

ii 70 to 90 °C. **[4]**

[Total: 12]

SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
explain what a catalyst is	B4.01			
explain why enzymes are said to be biological catalysts, and why they are important to sustain life	B4.01			
describe how enzymes work, using the terms *active site*, *substrate*, *complementary shape* and *product*	B4.01			
use the term *enzyme–substrate complex*	B4.01			
explain why enzymes are specific	B4.01			
describe how to investigate the effect of temperature and pH on enzyme activity, and describe these effects, using the words *optimum* and *denaturation*	B4.02			
explain the effect of temperature on enzyme activity, using the words *kinetic energy*, *frequency of effective collision*, *complementary shape* and *denaturation*	B4.02			
explain the effect of pH on enzyme activity, using the words *complementary shape* and *denaturation.*	B4.02			

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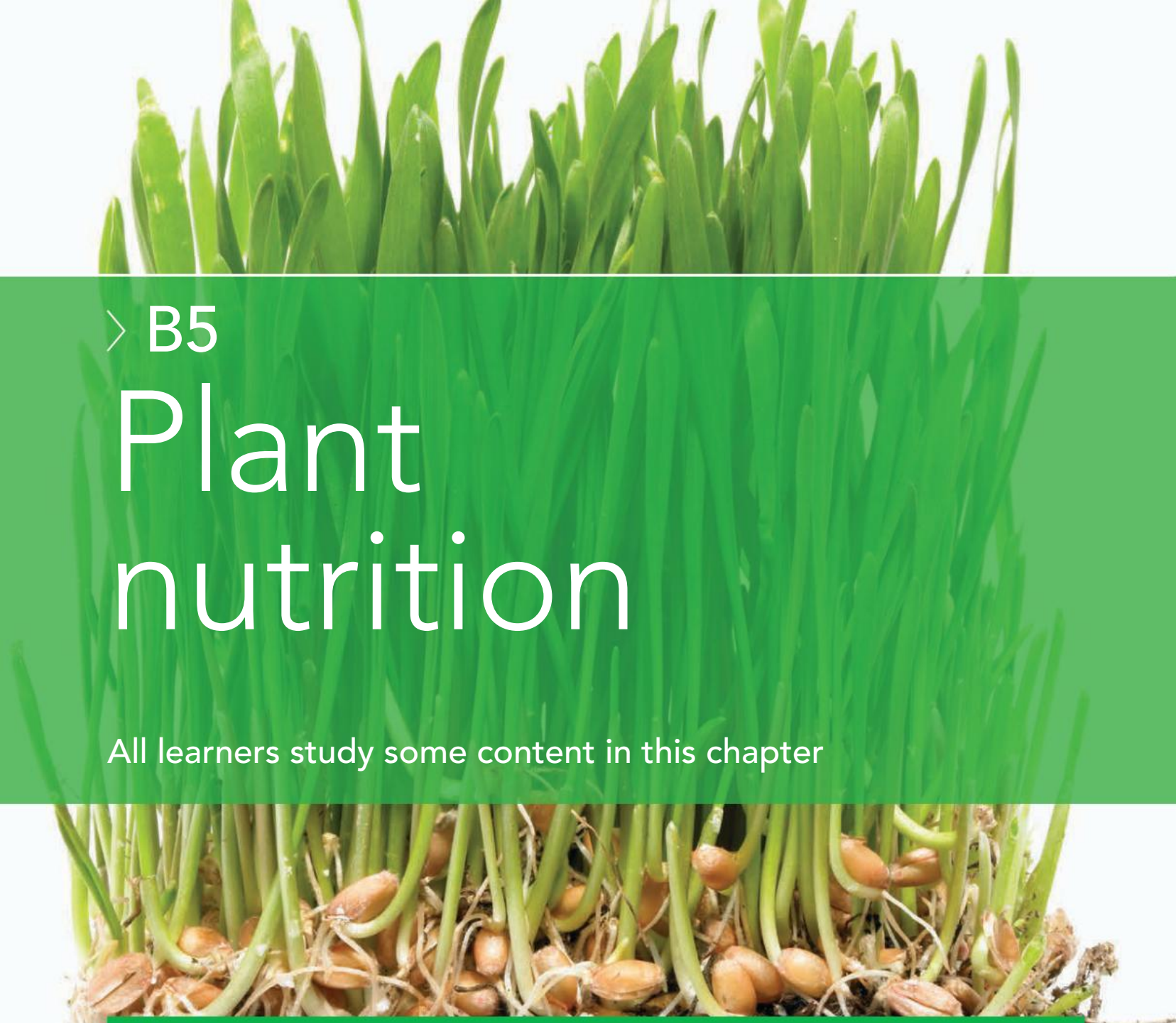

B5 Plant nutrition

All learners study some content in this chapter

IN THIS CHAPTER YOU WILL:

- learn about photosynthesis and the equation for it
- find out how plants use the carbohydrates made in photosynthesis
- learn how the structure of a leaf is adapted for photosynthesis
- investigate the need for chlorophyll, light and carbon dioxide in photosynthesis
- investigate how light and temperature affect the rate of photosynthesis
- find out how a plant uses glucose produced in photosynthesis
- learn about the functions of nitrate ions and magnesium ions in a plant
- identify structures of a the leaf in diagrams and images of a dicotyledonous plant
- learn how the features of a leaf are adaptations for photosynthesis.

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BEFORE YOU START

Work with a partner. Discuss the answers to the questions below, and be ready to share your ideas with the rest of the class.

1 What types of nutrient does your body use to obtain energy?
2 Energy cannot be created or destroyed. Where did the energy in the nutrients come from originally?
3 How did the energy get into the nutrients?

SCIENCE IN CONTEXT B5.01

Using solar energy to make fuels

As the human population continues to grow, we are using more and more fuel to provide energy for our homes, industries and vehicles. Good progress is being made in using more renewable energy sources, such as wind and solar power, but a lot of this energy still comes from fossil fuels.

Burning fossil fuels produces carbon dioxide and the quantity of carbon dioxide in the atmosphere is increasing. This contributes to global warming. We urgently need to find alternative ways of providing energy.

Can we take a lesson from plants? Plants use energy from sunlight to make carbohydrates, which provide energy for their cells. This way of providing useful energy does not produce carbon dioxide – it uses it up. Already, in many parts of the world, plants are being grown to provide us with biofuels that can be burnt to produce electricity, or to move vehicles. But this takes up a large amount of land that may be needed to grow food crops, or that would be better left as natural forests or other habitats for wildlife.

So, scientists are looking into ways in which we might use a kind of 'artificial photosynthesis' to make fuels.

Plants contain a substance called chlorophyll, which captures energy from sunlight and helps to transfer this energy into carbohydrates. Research into artificial photosynthesis is exploring other substances that might be able to perform the same role. One laboratory is using tiny particles of gold as a substitute for chlorophyll. It works, but only very slowly. Researchers think it will be at least 2030 before we are able to use artificial photosynthesis to produce significant quantities of fuel for the human population to use.

Discussion question

1 How might the large-scale use of artificial photosynthesis help to slow down climate change?

B5.01 Photosynthesis

All living organisms need to take many different substances – nutrients – into their bodies. Some of these may be used to make new parts or to repair old parts.

Others may be used to release energy. Taking in useful substances is called nutrition.

In Chapter B3, you saw that there are several important groups of biological molecules. These include proteins, fats and carbohydrates. These are all organic substances. Animals are not able to make organic substances themselves. They must take them in as nutrients when they feed.

Plants, however, can make these organic nutrients from inorganic substances. They use carbon dioxide, water and mineral ions, which they take in from the air and soil.

The process by which they make carbohydrates is called **photosynthesis**, which means 'making with light'.

KEY WORD

photosynthesis: the process by which plants synthesise carbohydrates from raw materials using energy from light.

The photosynthesis equation

In photosynthesis, water and carbon dioxide react together to produce glucose and oxygen. They will only do this in the presence of sunlight and chlorophyll.

We can write this reaction as a word equation:

$$\text{carbon dioxide} + \text{water} \xrightarrow[\text{chlorophyll}]{\text{sunlight}} \text{glucose} + \text{oxygen}$$

Like all reactions in organisms, photosynthesis depends on enzymes to help it take place.

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We can also write a balanced chemical equation, which includes the chemical formula for each of the reactants and products. It also provides information about how many molecules of each are involved in the reaction.

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$$

The formula CO_2 represents carbon dioxide, and it tells us that one molecule of carbon dioxide contains one atom of carbon, C, and two atoms of oxygen, O. The formula $C_6H_{12}O_6$ represents glucose. It tells us that one molecule of glucose contains 6 atoms of carbon, 12 atoms of hydrogen and 6 atoms of oxygen. So, six carbon dioxide molecules are needed to make one glucose molecule. There are the same number of atoms on each side of the equation.

Questions

B5.01 Explain why animals are dependent on plants for their supply of energy.

B5.02 Explain how chlorophyll helps photosynthesis to happen.

B5.03 How many glucose molecules can be made from 12 molecules of carbon dioxide and 12 molecules of water?

ACTIVITY B5.01

Modelling photosynthesis

Work in a group of four or five for this activity.

You will need:

- egg cartons cut into:
  - six shapes like Figure B5.01a
  - six shapes like Figure B5.01b
  - six shapes like Figure B5.01c
- one complete egg carton that can hold 12 eggs, labelled like Figure B5.01d
- 36 small balls that fit into the egg cartons – for example, table tennis balls
- red, black and blue pens to write on the balls.

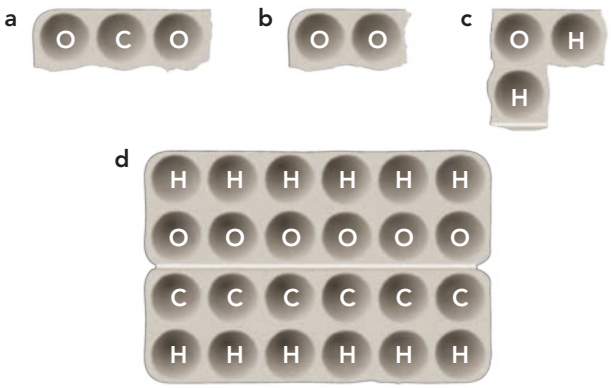

Figure B5.01: How to cut up and label your egg cartons.

Method

1. The small balls represent atoms.
   Use the red pen to label 18 of them 'O' or 'oxygen'.
   Use the black pen to label 6 of them 'C' or 'carbon'.
   Use the blue pen to label the other 12 'H', or 'hydrogen'.
2. Take one ball representing oxygen and two balls representing hydrogen, and put them into an angled box to make a water molecule (Figure B5.02).

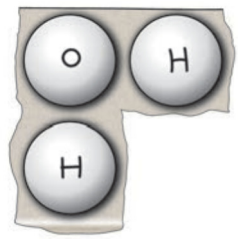

Figure B5.02: Modelling a water molecule.

3. Make five more water molecules.
4. Use the remaining balls to make six carbon dioxide molecules. (Make sure you choose the correct egg carton shapes for this.)
5. Now use your water molecules and carbon dioxide molecules to make a glucose molecule. Do this by putting the balls into the correct holes in the base and lid of the 12-hole egg carton. To do this, use oxygen from the water only. Do *not* use oxygen from the carbon dioxide.
6. Use your leftover balls to make oxygen molecules.
7. If you have time, take apart your glucose molecule and the oxygen molecules, and turn them back into carbon dioxide and water.

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CONTINUED

Questions

1 Explain how this model represents the balanced equation for photosynthesis.

2 Suggest how you could modify the model, or the way that you use the model, to show how energy in sunlight helps the reaction to take place.

3 You may hear people say that 'photosynthesis changes carbon dioxide into oxygen'. Use your model to explain why this is not correct.

Reflection

Some people find using a model like this, where you handle objects and move them around, helps them to understand. Did this model help you to understand the photosynthesis equation?

If it did, can you explain how it helped?

If it did not, is there a different method you might suggest people like you could use, to help them to understand?

Chlorophyll

In the chloroplasts of a plant's leaves, water and carbon dioxide react together to make carbohydrates and oxygen. In other circumstances, you could shine light on a mixture of carbon dioxide and water for ever, and no carbohydrates or oxygen would ever appear. What is special about a plant's leaves is that they contain a green pigment called chlorophyll. This is present in its chloroplasts.

Chlorophyll is able to capture energy from sunlight (Figure B5.03). When it has done this, it immediately passes the energy on (transfers it) to water molecules and carbon dioxide molecules. The energy makes these substances react, producing a kind of carbohydrate called glucose.

Figure B5.03: A forest is a giant carbohydrate factory, using sunlight as fuel and carbon dioxide and water as its raw materials.

The glucose that is made in the leaves contains some of the energy that was originally in the sunlight. Chlorophyll has transferred some of the energy in the sunlight into energy in carbohydrates.

How a plant uses carbohydrates

We have seen that there are two products of photosynthesis: glucose and oxygen. The oxygen is released into the atmosphere (or into the water if the plant is aquatic). The glucose (a carbohydrate) is used for many different purposes.

Releasing useful energy

Some of the glucose is used by the plant to provide energy for various activities that its cells need to carry out. For example, energy is needed to move mineral ions into the root hairs, by active transport. Energy is also needed to build protein molecules from amino acids, for growth.

The energy is released from glucose by respiration. You will find out about respiration in Chapter B9.

Storing, to use later

Plants usually make much more glucose than they need to use for energy immediately. They store it by turning it into starch.

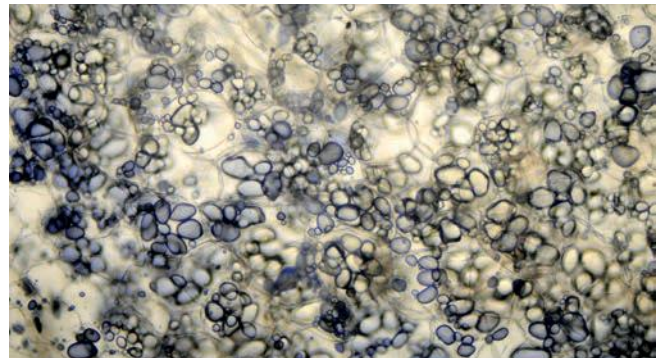

Figure B5.04: This is a photomicrograph of cells from a potato tuber. Iodine solution has been added so the starch grains are stained blue. You can see some cell walls if you look closely.

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Starch molecules are made by linking many glucose molecules together, to make a long, spiral chain. Millions of these molecules clump together to make starch grains (Figure B5.04). Starch molecules are not soluble in water, so they do not get involved in the chemical reactions taking place inside the plant cells. They also do not affect the concentration of the solutions inside the cell, so they do not cause water to enter or leave by osmosis. The starch molecules can quickly and easily be broken down to glucose molecules again when the plant needs them.

Making sucrose, for transport

Plants can only make glucose in the parts that contain chlorophyll, which usually means the leaves. All the other parts of the plant have glucose delivered to them. Plants, however, do not actually transport glucose. They first change it into a sugar with larger molecules, called **sucrose**. The sucrose is carried from one part of the plant to another inside tubes called phloem tubes. You can find more about this in Chapter B7.

When the sucrose reaches its destination, it can be changed back to glucose again, and used in respiration to release energy.

Making cellulose, to build cell walls

As plants grow, they make new cells. Every cell needs a cell wall, so a growing plant must make cellulose molecules to form these walls. Cellulose is made by linking glucose molecules in long chains. The molecules are linked in a different way from starch, so the chains stay straight rather than coiling up into spirals.

Making nectar, to attract pollinators

Many plants reproduce sexually, producing male and female gametes in flowers. Unlike animal gametes, the male gametes of flowers cannot move themselves from place to place. Instead, they rely on insects, bats or birds to carry them, inside **pollen grains**, from one flower to another (Figure B5.05). No animal is going to do this for a plant unless it gets a reward, so flowers produce **nectar** that animals can feed on. Nectar contains different kinds of sugar, all made from the glucose that the plant has made by photosynthesis.

Figure B5.05: Insects are attracted to flowers to collect the carbohydrate-rich nectar, and protein-rich pollen. Unknown to the insects, they help the flower by pollinating it.

Making amino acids, to make proteins

Plants use some of the glucose made in photosynthesis to make amino acids. These amino acids can then be used to make proteins, for growth.

You may remember that proteins contain not only carbon, hydrogen and oxygen, but also nitrogen. So, in order to make amino acids from glucose, plants need a source of nitrogen. They get this from the soil, in the form of nitrate ions. Usually, these ions are taken in by active transport, through the root hairs. The ions are transported to all parts of the plant, where they are combined with glucose to make amino acids.

If a plant cannot get enough nitrate ions, it will not be able to synthesise proteins effectively, and so will not grow quickly or strongly.

Making other substances, such as chlorophyll

Glucose can also be used to make chlorophyll. Chlorophyll is not a protein, but it does contain nitrogen. It also contains magnesium. Therefore, plants need to take in magnesium ions, as well as nitrate ions, to make chlorophyll. Without these ions, the plant's leaves will look yellow rather than the green we would expect when there is plenty of chlorophyll present (Figure B5.06). If a plant cannot make lots of chlorophyll, it will not be able to photosynthesise well, and therefore will not grow well.

KEY WORDS

sucrose: a sugar whose molecules are made of glucose and another similar molecule (fructose) linked together.

pollen grains: small structures which contain the male gametes of a flower.

nectar: a sweet liquid secreted by many insect-pollinated flowers, to attract their pollinators.

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Figure B5.06: These leaves are on an orange tree, growing in soil that does not contain enough magnesium ions. The tree cannot make enough chlorophyll, so the leaves are not completely green.

Questions

B5.04 Starch can easily be broken down to glucose by the enzyme amylase, which is found in plants. Cellulose is much more difficult to break down to glucose. Suggest how these differences between starch and cellulose relate to their functions in a plant.

B5.05 Animals do not make or store starch. What is the substance that animals store, which is made of chains of glucose molecules?

B5.06 Explain why some parts of a plant must have sucrose delivered to them.

B5.07 Copy and complete this table.

Element	_____	magnesium
Mineral salt	nitrate ions	magnesium ions
Why needed	to make _____, and then proteins	_____
Deficiency	weak growth, yellow leaves	yellowing of leaves, often especially between the veins

B5.08 Making nectar costs a plant energy because it uses up glucose that the plant has made. Explain why the expense is worthwhile.

B5.02 Leaves

Photosynthesis happens inside chloroplasts. This is where the enzymes and chlorophyll that catalyse and supply energy for the reaction are found. In a typical plant, most chloroplasts are in the cells in the leaves. A leaf is a factory for making carbohydrates.

It is, therefore, not surprising that most plants have leaves that are perfectly adapted to help photosynthesis to take place as quickly and efficiently as possible.

The structure of a leaf

A leaf consists of a broad, flat part (Figure B5.07), which is joined to the rest of the plant by a leaf stalk. Inside the leaf stalk are collections of parallel tubes called **vascular bundles**, which also form the veins in the leaf. The tubes in the vascular bundles carry substances to and from the leaf (Chapter B7).

Photosynthesis happens inside chloroplasts in the leaf cells. This is where the chlorophyll is found. The chlorophyll is spread out on membranes, so that a lot of sunlight can reach it.

KEY WORDS

vascular bundles: collections of xylem tubes and phloem vessels running side by side, which form the veins in a leaf.

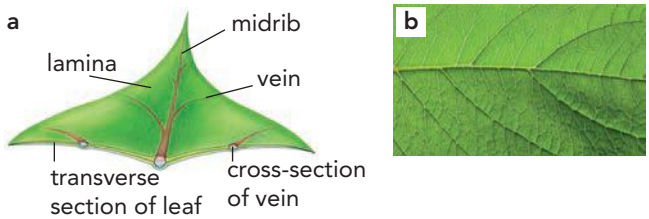

Figure B5.07 a: The structure of a leaf. **b:** The network of veins in this dicot leaf carries water to all parts of it.

You will remember that the raw materials for photosynthesis are carbon dioxide and water, and that sunlight is needed to provide energy. Most – but not all – leaves have a large surface area and are very thin. The large surface area allows large amounts of sunlight to fall onto the leaf. The large surface area also increases the rate at which carbon dioxide can diffuse into the leaf from the air. Only 0.04% of the air is carbon dioxide. So, the structure of a leaf must allow carbon dioxide to move into the leaf really easily.

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Because the leaf is thin, sunlight can pass right through it, allowing many cells inside it to photosynthesise. The thinness also helps carbon dioxide to reach all the cells quite quickly by diffusion.

Water is brought to the leaf from the soil, in tubes called xylem (pronounced zi-lem) vessels. These run in the vascular bundles, which form the veins in the leaf. You can often see many tiny veins in a leaf if you look closely.

Tissues in a leaf

Although a leaf is thin, it is made up of several layers of cells. You can see these if you look at a transverse section (TS) of a leaf under a microscope (Figure B5.09). Each tissue in a leaf has its own function.

Figure B5.08 summarises how the raw materials for photosynthesis – carbon dioxide and water – travel to a chloroplast in a palisade cell.

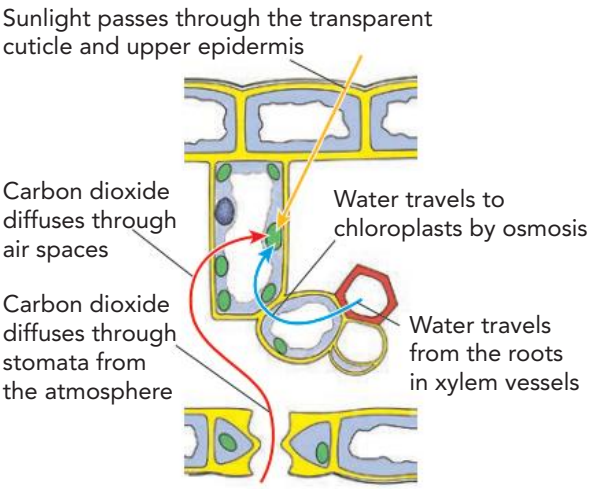

Figure B5.08: How the raw materials for photosynthesis get into a palisade cell.

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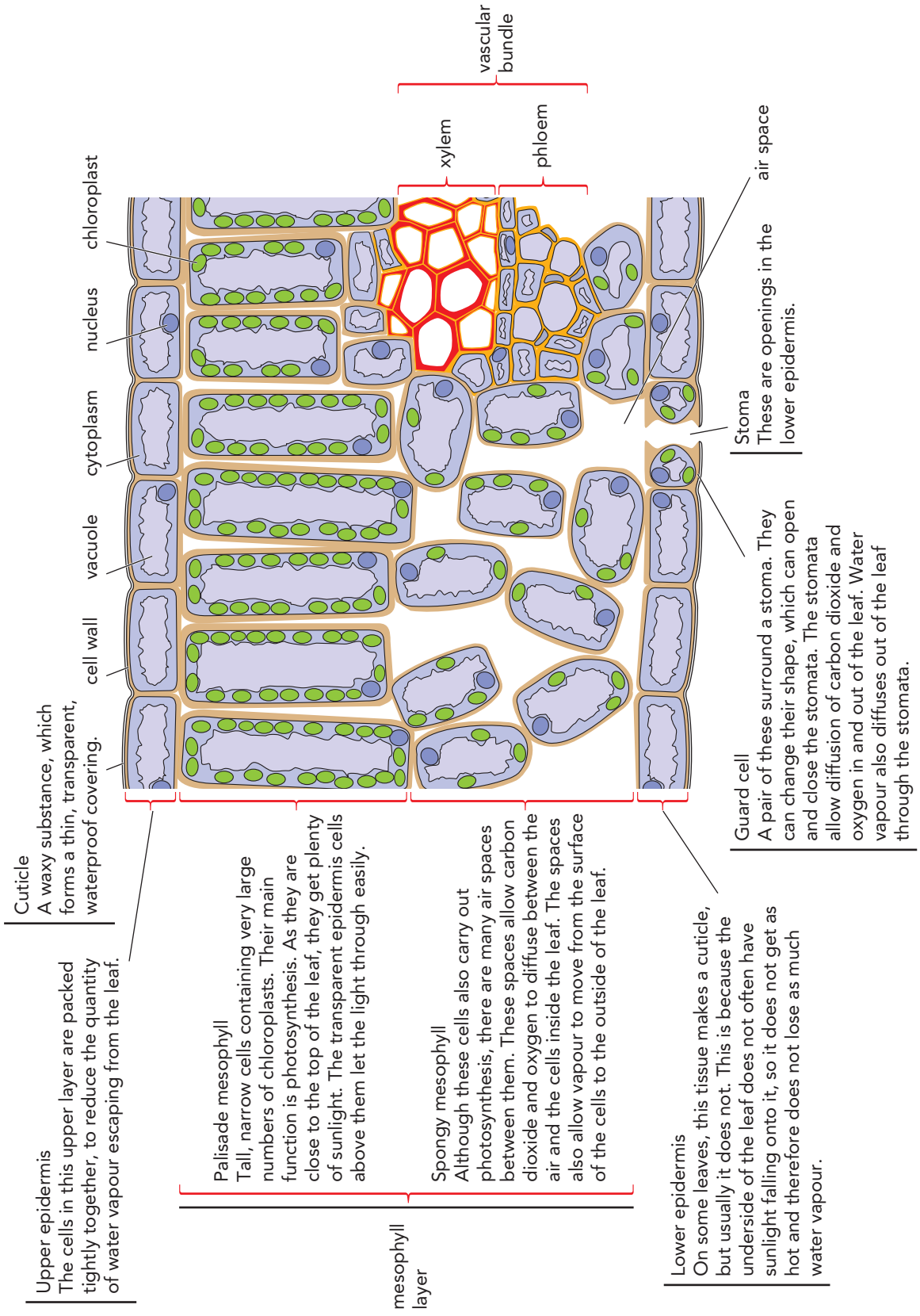

Figure B5.09: A diagram showing a transverse section through a leaf.

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Questions

B5.09 Figure B5.10 shows a photomicrograph (×400) of a small part of a leaf from a tea plant. Identify structures A–D.

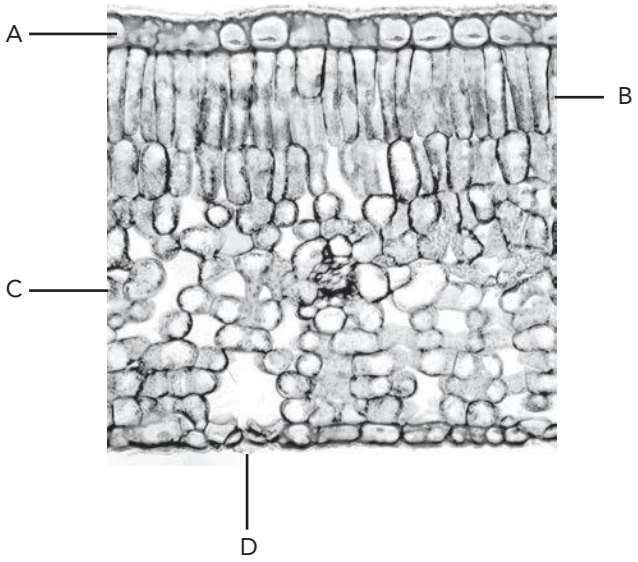

Figure B5.10: Photomicrograph of a small part of a leaf from a tea plant (×400).

B5.10 Explain how a palisade mesophyll cell is adapted for its function.

B5.11 Suggest why the cells in the lower epidermis of a leaf (apart from the guard cells) do not contain chloroplasts.

B5.03 Factors affecting photosynthesis

The rate at which photosynthesis happens is affected by several environmental factors. These include:

- the supply of the raw materials: carbon dioxide and water
- the quantity of sunlight, which provides energy for the reactions
- the temperature, because this affects the activity of enzymes.

As well as these environmental factors, the quantity of the chlorophyll in the leaf also helps to determine how fast photosynthesis can take place.

In this topic, you will investigate how each of these factors affects the rate of photosynthesis.

EXPERIMENTAL SKILLS B5.01

Testing a leaf for starch

Leaves turn some of the glucose that they make by photosynthesis into starch. If we find starch in a leaf, that tells us it has been photosynthesising. In this experiment, you will practise working safely, making careful observations and drawing conclusions.

You will need:

- a 250 cm^3 beaker
- a burner, tripod and gauze
- a boiling tube
- some iodine solution, with a dropper
- forceps
- a glass rod
- some alcohol (methylated spirits) – collect this only when you are ready to use it
- a fresh green leaf that has been photosynthesising
- a white tile.

Safety

Alcohol is flammable (burns easily).

Do not collect the alcohol until you have turned off your burner.

If your alcohol (or someone else's) does start to burn, put a damp cloth over it immediately.

Method

1. Boil some water in a beaker (Figure B5.11).
   Take a green leaf from a healthy plant and drop it into the boiling water. This breaks down the cell membranes in the leaf. Leave the leaf in the boiling water for about 30 seconds.
2. Turn off the flame.
3. Put some alcohol into a boiling tube. Stand the tube of alcohol in the hot water.
4. Use the forceps to remove the softened leaf from the hot water. Drop it into the tube of alcohol. Chlorophyll is soluble in alcohol, so it will come out of the leaf. Leave the leaf in the alcohol until all the chlorophyll has come out of the leaf.

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CONTINUED: B5.01

5 The leaf will now be brittle (it will break easily). Carefully remove it from the alcohol, and dip it into hot water again to soften it.

6 Spread out the leaf on a white tile and cover it with iodine solution. A blue–black colour shows that the leaf contains starch.

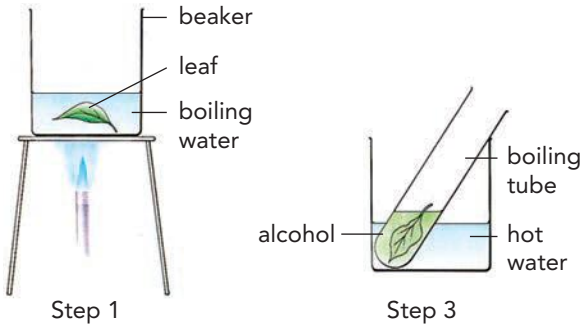

Figure B5.11: Testing a leaf for starch.

Questions

1 Describe the results of your experiment. What conclusion can you make?

2 Cell membranes are partially permeable. They will not allow starch or iodine molecules to pass through them. Use this information to explain why it was necessary to boil the leaf.

3 Suggest why it is a good idea to remove the chlorophyll from the leaf, before adding iodine solution to it.

EXPERIMENTAL SKILLS B5.02

Investigating the necessity for chlorophyll for photosynthesis

In this investigation, you will use the starch test again. A variegated leaf is one that has some white areas and some green areas (Figure B5.12). You will practise recording your observations with a labelled drawing.

You will need:

- the same apparatus as for Experimental skills B5.01 Testing a leaf for starch
- a fresh variegated leaf, taken from a plant that has been photosynthesising.

Safety

Alcohol is flammable (burns easily).

Do not collect the alcohol until you have turned off your burner.

If your alcohol (or someone else's) does start to burn, put a damp cloth over it immediately.

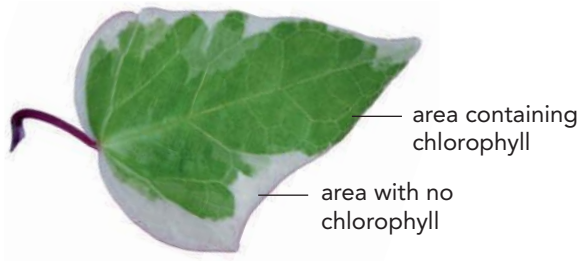

Figure B5.12: A variegated leaf.

Method

1 Make a drawing of your variegated leaf. Do not colour it. Label the parts that are green and the parts that are white.

2 Test the leaf for starch, following the procedure described in Experimental skills B5.01.

3 Record your results by drawing and labelling the leaf after you have added iodine solution to it.

Questions

1 Which parts of the leaf contained starch?

2 Write a brief conclusion for your experiment.

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EXPERIMENTAL SKILLS B5.03

Investigating the necessity for light for photosynthesis

In this investigation, you will use the starch test to compare the starch content of parts of a leaf that have received light and parts that have not. This is another chance to practise recording results using a labelled drawing, and to write a short conclusion.

You will need:

- a healthy plant growing in a pot, which has been in a dark cupboard for two days
- some black paper, scissors and paper clips
- (after one day) the same apparatus as for Experimental skills B5.01 Testing a leaf for starch.

Safety

Alcohol is flammable (burns easily).

Do not collect the alcohol until you have turned off your burner.

If your alcohol (or someone else's) does start to burn, put a damp cloth over it immediately.

Method

1 Cut out a shape from the black paper, which you can attach to a leaf. If you like, you can cut your initials into the paper (Figure B5.13).

2 Attach the paper to a leaf on the potted plant. Do not take the leaf off the plant!

3 Put the plant into a place where it gets plenty of light. Leave it until the next day.

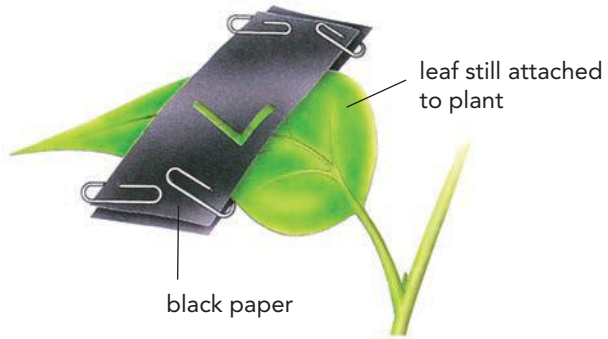

Figure B5.13: Using black paper to block light from reaching part of a leaf.

4 Now remove the leaf from the plant. Remove the black paper from the leaf.

5 Test the leaf for starch.

6 Record your results by drawing and labelling the leaf after you have added iodine solution to it.

Questions

1 The potted plant was put into a cupboard to make sure it used up all its starch stores and had no light to be able to make more. This is called **destarching**. Suggest why this was a necessary part of this experiment.

2 Explain why, in this experiment, the leaf had to remain attached to the plant for a day, after you put the black paper onto it.

3 Use your results to write a short conclusion to your experiment.

KEY WORD

destarching: leaving a plant in the dark for long enough for it to use up its starch stores.

Controls

In Experimental skills B5.03, you wanted to find out whether light was needed for photosynthesis. To do this, you needed to be able to compare a part of a leaf that did have light with a part that did not have light.

The part of the leaf that you did not cover was the **control** in your experiment. It allowed you to compare the part that did not have light with this normal part, which did.

If you had covered all the leaf, and found that none of it photosynthesised, you would not be sure that the reason was because it had no light. It could have been because the whole plant was not photosynthesising.

In Experimental skills B5.02, you wanted to find out whether chlorophyll was needed for photosynthesis. The white parts of the leaf had no chlorophyll, and you could compare these with the normal, green parts. These green parts were the control in this experiment.

KEY WORD

control: a standard sample that you use as a comparison, to find the effect of changing a variable.

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EXPERIMENTAL SKILLS B5.04

Investigating the necessity for carbon dioxide for photosynthesis

In this investigation, you will compare the ability of two leaves on the same plant – one with carbon dioxide and one without – to make starch. This is not an easy experiment to set up, so you will probably just use one set of apparatus for the whole class.

You will need:

- a healthy plant growing in a pot, which has been destarched (see Experimental skills B5.03)
- two transparent containers, e.g. conical flasks
- two rubber bungs to fit the flasks, each with a slit in one edge in which a leaf stalk can fit
- petroleum jelly
- a method of supporting the transparent containers
- some potassium hydroxide solution
- some distilled water
- (after one day) the same apparatus as for Experimental skills B5.01 Testing a leaf for starch.

Safety

Alcohol is flammable (burns easily).

Do not collect the alcohol until you have turned off your burner.

If your alcohol (or someone else's) does start to burn, put a damp cloth over it immediately.

Method

1 Set up the apparatus as shown in Figure B5.14. Note that you will have to find a way of supporting the flasks so that they do not pull on the leaves. You could use a retort stand and clamps. Once you have that organised, put the liquids into the two flasks. Next, hold one of the leaf stalks carefully, and slot it into one of the rubber bungs. Then gently push the flask over the bung and into its support. Repeat with the other leaf and flask.

2 Rub petroleum jelly over the rubber bungs, to try to prevent any air entering or leaving the flask.

3 Place the apparatus in a light place and leave it for at least one day.

4 Test both leaves for starch.

5 Record your results.

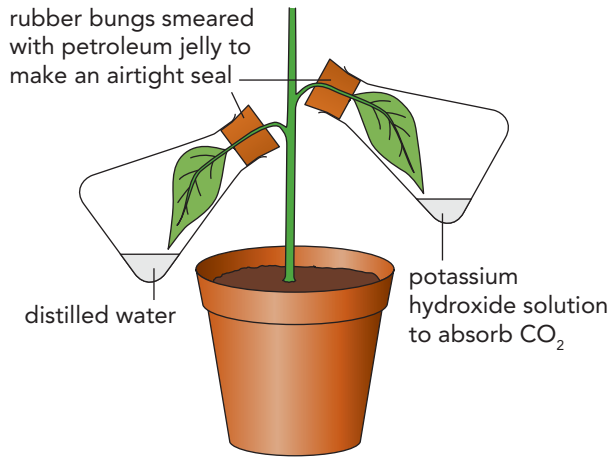

Figure B5.14: Using potassium hydroxide solution to remove carbon dioxide from around a leaf.

Questions

1 What was the control in this experiment?

2 Suggest why distilled water was added to one flask, rather than just leaving it empty.

3 Write a short conclusion for your experiment.

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EXPERIMENTAL SKILLS B5.05

Investigating the effect of varying light intensity on the rate of photosynthesis

In this experiment, you will use an aquatic plant.
An aquatic plant is one that lives in water. This makes it easy to measure the rate of photosynthesis, because we can see bubbles of oxygen being released into the water. In order to measure a rate, we need to measure how much oxygen is given off in unit time – that is, a definite length of time, such as one minute.

You will need:

- a healthy aquatic plant, which has been in the light and has been photosynthesising
- the apparatus shown in Figure B5.15
- a paperclip
- a lamp
- a ruler to measure the distance between the lamp and the plant
- a stopwatch or timer.

Safety

Keep water away from the lamp.

Before you start

1 Check that you know how to use your stopwatch or timer, and that it is working properly.

Method

1 Collect a piece of aquatic plant. Cut off a piece about 7 to 9 cm long. Work out which way up it is. Attach a paperclip to the top of it.

2 Set up the apparatus as shown in Figure B5.15. The paperclip will hold the top of the plant down, so that its cut end floats upwards.

3 Place the lamp as close as possible to the beaker. Measure the distance, and record it in a results table like this:

Distance of lamp from beaker / cm	Number of bubbles produced in one minute			
	1st try	2nd try	3rd try	Mean

4 Start the stopwatch or timer. Count the number of bubbles released from the cut end of the stem in one minute. Record this, and then repeat two more times.

5 Move the lamp a little bit further from the plant. Measure the new distance, and repeat step 4.

6 Repeat step 5 several times, until you have bubble counts for at least five different distances. Do more if you have time.

7 Plot your results as a line graph, with distance on the *x*-axis and mean number of bubbles on the *y*-axis. Make sure that the two axes are labelled fully, and that you choose suitable scales. Join the points using ruled, straight lines between the points.

Questions

1 Explain why an aquatic plant was used in this experiment.

2 Light intensity decreases as the distance of the lamp from the beaker increases. Write a conclusion to summarise what your results show about the effect of light intensity on the rate of photosynthesis.

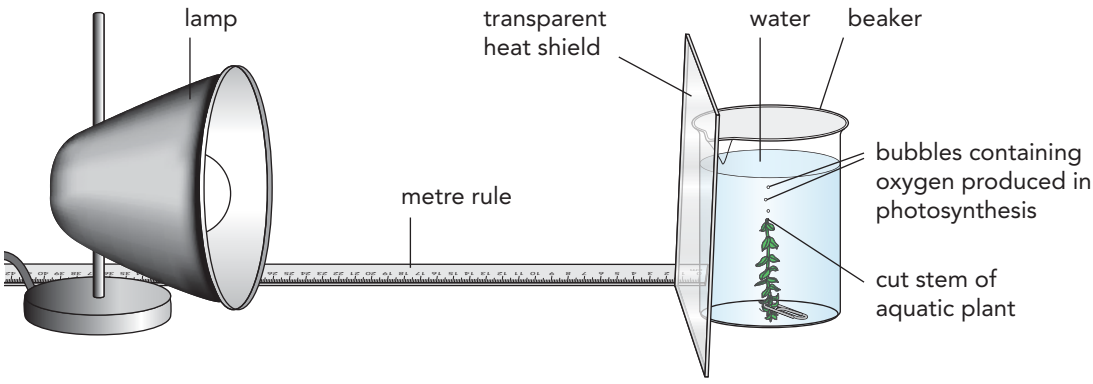

Figure B5.15: Apparatus for Experimental skills B5.05.

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CONTINUED: B5.05

3 Lamps produce heat as well as light. Explain why you would be unable to draw a conclusion about light intensity, if you did not use a heat shield.

4 It is possible to collect the gas given off by the plant and measure its volume. Suggest why this would be an improvement on the method you have used here.

Self assessment

Give yourself a mark according to the following scheme for each of the features of your graph listed below.

2 marks if you did it really well

1 mark if you made a good attempt at it and partly succeeded

0 marks if you did not try to do it, or did not succeed

- The axes are both fully labelled, including units.
- The scales on both axes go up in even steps.
- The scales use at least half of the graph paper.
- The points are plotted as small, neat crosses in exactly the right place.
- The lines between the points are drawn with a ruler, and exactly meet the centres of the crosses.

How many marks do you give yourself out of 10? What will you do next time you draw a line graph, to increase your score?

EXPERIMENTAL SKILLS B5.06

Investigating the effect of temperature and carbon dioxide on the rate of photosynthesis

In this experiment, you will use a similar method to Experimental skills B5.05. This time, however, your independent variable will be either carbon dioxide concentration or temperature. You are going to plan your own experiment.

You will need:

- the apparatus used in Experimental skills B5.05
- electric water-baths, or access to ice and hot water, and a thermometer.

Method

1 Think about how you will vary temperature. You can vary temperature by standing the beaker in a water-bath at different temperatures, or by adding ice and hot water to the water around the plant. You should aim to have at least five values of your independent variable.

2 Think about other variables that you should try to keep constant, and how you will do this.

3 Write out your plan. You could structure it like this:
   - Independent variable and how you will vary it.
   - Values of the independent variable you will use.
   - Variables that you will keep constant, and how you will do this.
   - The variable that you will measure, and how you will do this.
   - Possible safety risks, and how you will minimise them.
   - An outline results chart, ready to complete as you work.

4 If possible, exchange your plan with another person in your class who is investigating the other variable. Give them feedback on their plan. Use their feedback to you to make improvements to your own plan.

5 When you are ready, carry out your experiment and record your results.

Questions

1 Plot a line graph to display your results.

2 Write a short conclusion.

3 You probably encountered some difficulties or problems as you did your experiment. What were they, and how did you overcome them?

4 If you could start again, and had lots of time available, what improvements would you make to your experiment?

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PROJECT B5.01 DESIGNING A GLASSHOUSE

Work in a group of three or four for this activity. You might like to assign different roles to different people (e.g. organiser, researcher, communicator and so on).

You are going to design a glasshouse to grow a crop in your country. The glasshouse will provide ideal conditions to help the plants to photosynthesise quickly and grow fast, so that they will provide a high yield for the grower. Your group will then give a presentation to the rest of the class.

Here are some things to think about and research:

- What crop will you grow in the glasshouse?
- What conditions does this crop need to grow well?
- How can a glasshouse provide better conditions for the crop, than if it was grown outside?
- How will you control temperature in the glasshouse? In your country, will you need to heat the glasshouse, or cool it, or do both at different times?
- How will you control light in the glasshouse? In your country, will you need to give extra light, or might you need to shade the glasshouse sometimes?
- How will you provide carbon dioxide in the glasshouse? Providing carbon dioxide costs money, so what might be a suitable concentration to aim for, that will give you a good return for your expenditure?

You can make your presentation as a video, use PowerPoint or make models and draw diagrams – or all of these methods if you like.

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SUMMARY

Photosynthesis is a reaction in which plants make carbohydrates from carbon dioxide and water, using light as a source of energy.
The word equation for photosynthesis is: carbon dioxide + water → glucose + oxygen
The balanced equation is: $6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$
Chlorophyll is a green pigment present in the chloroplasts of some plant cells.
Chlorophyll transfers energy from light into energy in carbohydrates.
The carbohydrate glucose is made in photosynthesis. It can be used to release energy in respiration. Glucose can be used to make starch for storage of energy and sucrose for transport.
Glucose can be used to make amino acids and proteins, using nitrogen obtained from nitrate ions. It can also be used to make chlorophyll, using nitrogen and also magnesium ions.
Cellulose is used to build cell walls, sucrose is used for transport in the phloem, and nectar attracts insects for pollination.
Leaves have a large surface area, to capture energy from sunlight and to increase absorption of carbon dioxide from the air. Stomata on the lower surface allow carbon dioxide to diffuse into the air spaces, and then to the cells in the palisade mesophyll layer, where most photosynthesis takes place.
To test a leaf for starch, it is first boiled to break down cell membranes, then heated in alcohol to remove the chlorophyll. Finally, iodine solution is added.
We can use the starch test to show that leaves, or parts of a leaf, that do not have light, chlorophyll or carbon dioxide are not able to photosynthesise and make starch. Controls are needed so that we can compare the results with them.
We can use an aquatic plant to measure the rate of photosynthesis, by counting the number of bubbles given off in unit time, or by measuring the volume of gas given off in unit time.
This method, using an aquatic plant, can be used to investigate the effect of altering light intensity, temperature or carbon dioxide concentration on the rate of photosynthesis.

PRACTICE QUESTIONS

1 **Identify** the raw materials required for photosynthesis.

A carbon dioxide and oxygen
B oxygen and glucose
C glucose and water
D water and carbon dioxide **[1]**

COMMAND WORD

identify: name/select/recognise.

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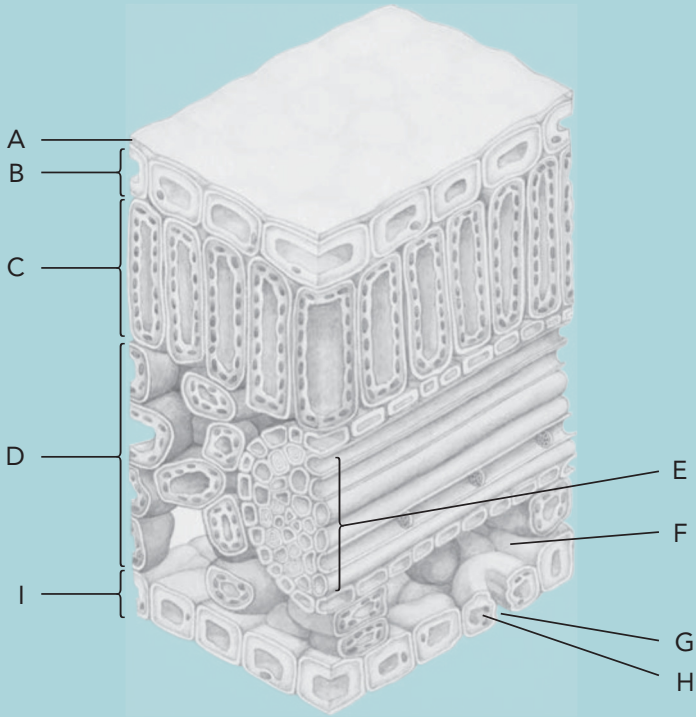
CONTINUED

2 Identify which ion a plant requires to make amino acids from glucose.

A calcium
B iron
C magnesium
D nitrate **[1]**

3 The diagram shows a three-dimensional drawing of a section through a leaf.



a i Identify the tissue labelled C. **[1]**

ii **Outline** how this tissue is adapted for its function. **[2]**

b **Give** the letters of *two* cells or tissues that do *not* contain chloroplasts. **[2]**

c **Describe** the function of the cell labelled H. **[2]**

d Use the letters on the diagram to describe how water reaches a chloroplast in the leaf. **[2]**

[Total: 9]

COMMAND WORDS

outline: set out main points.

give: produce an answer from a given source or recall/memory.

describe: state the points of a topic/give characteristics and main features.

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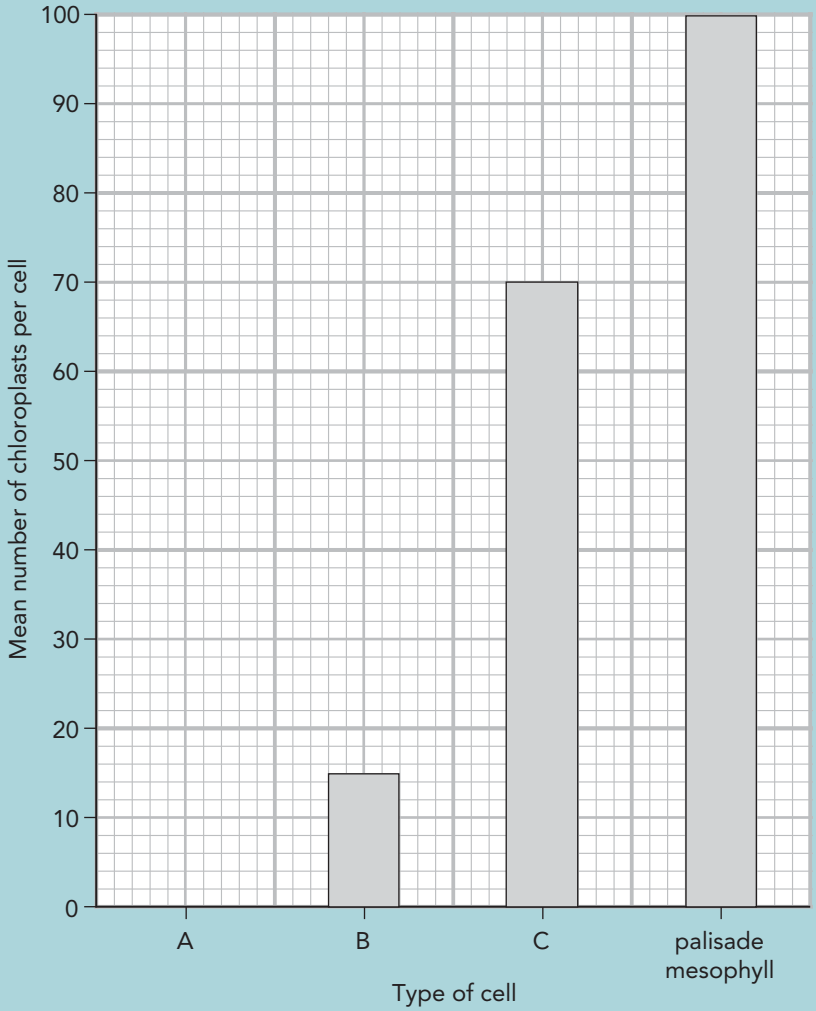
4 The bar chart shows the mean number of chloroplasts in four different types of cell in a leaf.



a **Explain** why palisade mesophyll cells have so many chloroplasts. **[2]**

b State which cell could be a cell in the upper epidermis. Explain your answer. **[2]**

c Guard cells contain chloroplasts, but not as many as spongy mesophyll cells. **Suggest** which cell could be a guard cell. **[1]**

d Chloroplasts contain chlorophyll. Describe the function of chlorophyll in photosynthesis. **[2]**

[Total: 7]

5 **a** Describe how plants synthesise carbohydrates. **[4]**

b Outline *two* subsequent uses of the carbohydrates made in photosynthesis. **[4]**

[Total: 8]

COMMAND WORDS

explain: set out purposes or reasons/make the relationships between things clear/provide why and/or how and support with relevant evidence.

suggest: apply knowledge and understanding to situations where there is a range of valid responses in order to make proposals/put forward considerations.

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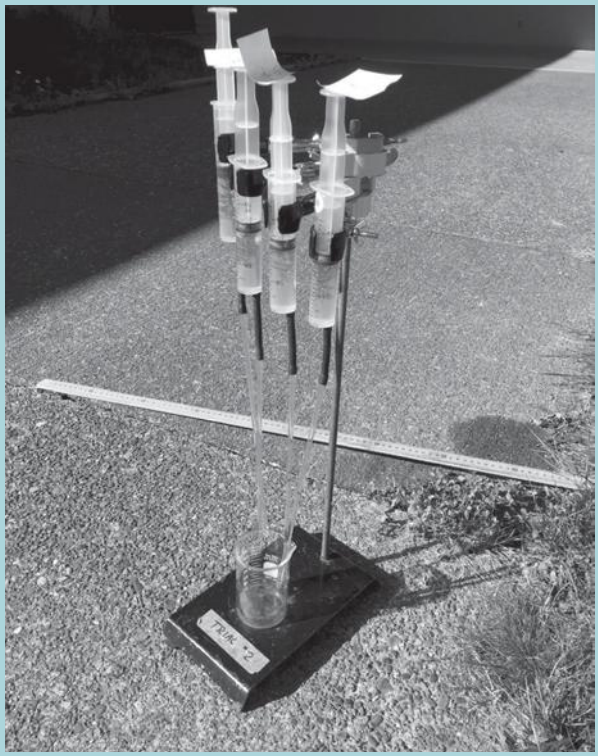
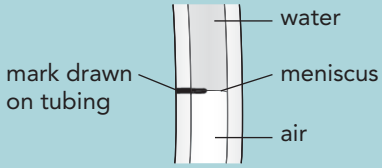
6 Two students carried out an experiment to investigate the effect of carbon dioxide concentration on the rate of photosynthesis of an aquatic plant. The photograph shows some of the apparatus that they used.



- The students filled five syringes with five different concentrations of sodium hydrogencarbonate solution. This provides carbon dioxide.
- They placed a piece of aquatic plant in each syringe.
- They attached a long transparent tube to the nozzle of each syringe.
- They pushed the plunger of each syringe in a little way, to force some of the sodium hydrogencarbonate into the tubing.
- They then pulled each plunger out a little way, to introduce some air into the tubing.
- They marked the position of the meniscus on each piece of tubing, as shown in the diagram.



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CONTINUED

All five syringes were then placed in bright sunshine. As the plants photosynthesised, they released oxygen. The oxygen gas collected above the liquid in the syringe. This pushed the liquid down the tube.

The students recorded the distance moved by the meniscus in each piece of apparatus after 30 minutes.

a Identify the independent variable and the dependent variable in this investigation. **[2]**

b Explain why the five syringes were placed in bright sunshine. **[2]**

The table shows the results of the experiment.

Percentage concentration of sodium hydrogencarbonate solution	0	0.1	0.2	0.3	0.4
Distance moved by meniscus after 30 minutes / mm	5	8	12	14	17

c Draw a line graph to display these results. Join the points with ruled straight lines. **[5]**

d Explain the results of this investigation. **[2]**

e **i** Suggest *two* possible sources of error in this investigation. **[2]**

ii Suggest how the investigation could be modified to reduce these sources of error. **[2]**

[Total: 15]

SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
state the word equation for photosynthesis	B5.01			
write the balanced equation for photosynthesis	B5.01			
describe the role of chlorophyll in transferring energy from light to carbohydrates, in photosynthesis	B5.01			
outline the uses of starch, cellulose, sucrose and nectar, made from the carbohydrates made in photosynthesis	B5.01			
state the functions of nitrate ions and magnesium ions in a plant	B5.01			
name the different cell types and layers of a leaf	B5.02			

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CONTINUED

I can	See topic . . .	Needs more work	Almost there	Confident to move on
explain how the features of a leaf are adaptations for photosynthesis	B5.02			
describe how to investigate the necessity for chlorophyll, light and carbon dioxide for photosynthesis	B5.03			
explain what a control is, in an experiment	B5.03			
describe how to investigate the effect of varying light intensity and temperature on the rate of photosynthesis of an aquatic plant.	B5.03			

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B6 Human nutrition

All learners study some content in this chapter

IN THIS CHAPTER YOU WILL:

- learn about a balanced diet
- find out about the structure and function of the digestive system
- learn how and where physical and chemical digestion happen
- practise summarising information using an annotated drawing
- learn how and where enzymes and other secreted substances function in the digestive system.

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BEFORE YOU START

First, think on your own about the answers to these questions about biological molecules. Then discuss your ideas with a partner.

Be ready to share your ideas.

1 What type of biological molecule is starch?
2 What are the smaller units that a starch molecule is made of?
3 What are the smaller units that a protein molecule is made of?
4 Lipase is an enzyme that digests fats. What are the products of this reaction?
5 What type of biological molecule is lipase?

SCIENCE IN CONTEXT B6.01

Stomach acid

Figure B6.01 shows the inside of a healthy human **stomach**. The picture was taken using a tiny camera on the end of a tube that can be passed down the **oesophagus** and into the stomach.

The stomach is a very important part of the digestive system. It has strong, muscular walls, which help to break up food that you have swallowed and mix it with liquids. The folded walls of the stomach produce a liquid called gastric juice. This juice contains hydrochloric acid and enzymes that break down protein molecules and can kill many of the microorganisms in the food that we swallow.

Discussion question

1 The stomachs of some carnivorous animals, such as lions and hyenas, **secrete** more concentrated acid than we do. Can you suggest how this may help them to survive?

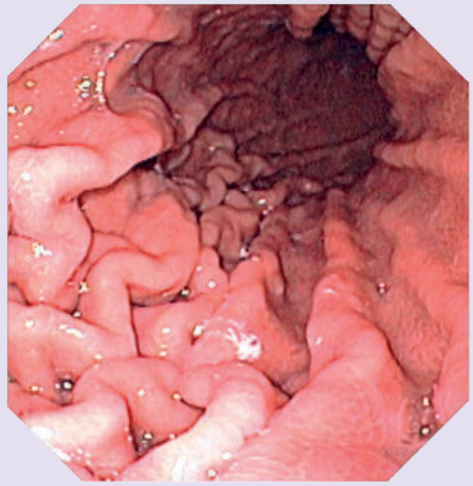

Figure B6.01: The inside of a healthy human stomach.

KEY WORDS

stomach: a wide part of the alimentary canal, in which food can be stored for a while, and where the digestion of protein begins.

oesophagus: the tube leading from the mouth to the stomach.

secrete: make a useful substance and then send it out of the cell where it is made, to be used in another part of the body.

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B6.01 Diet

Food provides us with energy. Depending on your sex or time of life, your energy requirements differ (Figure B6.02).

The food an animal eats every day is called its **diet**. Humans need six types of nutrient in their diet.

These are:

- carbohydrates
- proteins
- minerals
- fats
- vitamins
- water.

In addition, the diet should contain fibre (roughage). This is not really a nutrient, as it is not absorbed into the body. It just passes straight through the digestive system and is passed out in the faeces.

A diet which contains all of these things, in the correct amounts and proportions, is called a **balanced diet**. A person will get the necessary amount of energy if they eat a balanced diet.

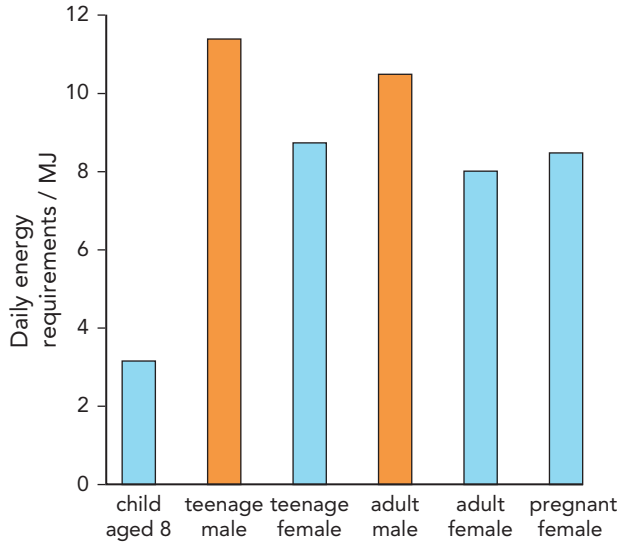

Figure B6.02: Daily energy requirements.

KEY WORDS

diet: the food eaten in one day.

balanced diet: a diet that contains all of the required nutrients, in suitable proportions, and the right amount of energy.

Nutrients

As well as providing you with energy, food is needed for many other reasons. To make sure that you eat a balanced diet, you must eat foods containing carbohydrate, fat and protein. You also need each kind of vitamin and mineral, fibre and water. If your diet does not contain all of these substances, your body will not be able to work properly.

Carbohydrates

Carbohydrates are needed for energy. Carbohydrates include starch and sugar. In most countries, there is a staple food that supplies much of the carbohydrate in people's diets, in the form of starch. Staple foods include potatoes, wheat (often made into bread or pasta), rice and maize (Figure B6.03). We also eat carbohydrate in sweet foods, which contain sugar.

Figure B6.03: Some good sources of carbohydrate.

Fats and oils

Fats and oils are needed for energy, and to make cell membranes. We store excess fat and oil under the skin, in adipose tissue. Here, it acts as an insulator, reducing heat loss from the body to the air. It can also form a layer around body organs such as the kidneys, providing mechanical protection for them. We obtain fat from cooking oils, meat, eggs, dairy products and oily fish (Figure B6.04).

Figure B6.04: Some good sources of fats and oils.

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Proteins

Proteins are needed to build new cells, for growth. They are also used to make proteins, including haemoglobin, insulin (a hormone) and antibodies (which help to destroy pathogens). We get protein from meat, fish, eggs, dairy products, peas and beans, nuts and seeds (Figure B6.05).

Figure B6.05: Some good sources of protein.

Vitamins

Vitamins are organic substances which are only needed in tiny amounts. If you do not have enough of a vitamin, you may get a deficiency disease. Table B6.01 shows information about sources and uses in the body of vitamins C and D.

	Vitamin	
	C	D
Foods that contain it	citrus fruits (such as oranges, limes), raw vegetables	butter, egg yolk (but most of our vitamin D is made by the skin when sunlight falls on it)
Why it is needed	to make the stretchy protein collagen, found in skin and other tissues; keeps tissues in good repair	helps calcium to be absorbed, for making bones and teeth
Deficiency disease	scurvy, which causes pain in joints and muscles, and bleeding from gums and other places; this used to be a common disease of sailors, who had no fresh vegetables during long voyages	rickets, in which the bones become soft and deformed; this disease was common in young children in industrial areas, who rarely got out into the sunshine

Table B6.01: Vitamins C and D.

Minerals

Minerals are inorganic substances. Once again, only small amounts of them are needed in the diet. Table B6.02 gives information about the sources and uses of two of the most important minerals.

Mineral ion	Foods that contain it	Why it is needed
calcium	milk and other dairy products, bread	for bones and teeth; for blood clotting
iron	liver, red meat, egg yolk, dark green vegetables	for making haemoglobin, the red pigment in blood which carries oxygen

Table B6.02: Calcium and iron.

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Fibre

Fibre helps to keep the **alimentary canal** working properly. The alimentary canal is the part of the digestive system through which food passes as it moves from the mouth to the **anus**. Food moves through the alimentary canal (see Topic B6.02) because the muscles contract and relax to squeeze it along. This is called **peristalsis**. The muscles are stimulated to do this when there is food in the alimentary canal. Soft foods do not stimulate the muscles very much. The muscles work more strongly when there is harder, less digestible food, like fibre, in the alimentary canal. Fibre keeps the digestive system in good working order and helps to prevent constipation.

All plant foods, such as fruits and vegetables, contain fibre (Figure B6.06). This is because plant cells have cellulose cell walls. Humans cannot digest cellulose.

One excellent source of fibre is the outer husk of cereal grains, such as oats, wheat and barley. This is called bran. Some of this husk is found in wholemeal bread. Brown or unpolished rice is also a good source of fibre.

Figure B6.06: Some good sources of fibre (roughage).

KEY WORDS

alimentary canal: part of the digestive system; a long tube running from mouth to anus.

anus: the exit from the alimentary canal, through which faeces are removed.

peristalsis: rhythmical muscular contractions that move food through the alimentary canal.

Water

More than 60% of the human body is water. Water is an important solvent. Cytoplasm is a solution of many substances in water. The spaces between our cells are also filled with a watery liquid.

Inside our cells, chemical reactions are happening all the time. These are called metabolic reactions. They can only take place if the chemicals that are reacting are in solution. If a cell dries out, then the reactions stop, and the cell dies.

The liquid part of blood is called plasma (Chapter B9). Plasma is also mostly water. It contains many dissolved substances, which are transported around the body in the blood. Water is also needed to dissolve enzymes and nutrients in the alimentary canal, so that digestion can take place.

We also need water to get rid of waste products. The urea is dissolved in water to form urine.

We get most of our water by drinking fluids, but some foods such as fruit also contain a lot of water.

ACTIVITY B6.01

A balanced diet in your country

You are going to work as a group to construct a balanced diet, by thinking about foods that are commonly eaten in your country.

In your group, discuss the foods that people eat in your country. Decide which ones are good sources of each kind of nutrient.

Construct a simple menu for the meals someone will eat in a day. Make sure that all the different nutrients are contained in the food. Do not forget to include drinks as well.

If you can, collect these foods together and take photographs of the meals, or the ingredients from which they would be made.

Question

B6.01 Construct a table showing the main dietary sources of carbohydrate, fat and protein, and their uses in the body.

REFLECTION

Some people find that summarising facts in a table – as in Question B6.01 – helps them to learn and remember the information. Does that work for you? Is it better if you construct the table yourself or if you just learn a table that is given to you?

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B6.02 Digestive system

You may remember that a body system, such as the **digestive system**, is a group of organs that work together to perform a particular function. The human digestive system includes the alimentary canal and also the **liver** and the **pancreas**. All of these work together to break down the food that we eat, so that the nutrients can be **absorbed** into the blood and delivered to all body cells.

The digestive system deals with the food in a series of processes, from **ingestion**, and **assimilation**, to egestion, as shown in Figure B6.07.

The processes of **chemical digestion** and physical digestion are described in Topic B6.03. To begin with, we will look at the structure of the alimentary canal, and outline what happens in each part.

KEY WORDS

digestive system: the group of organs that carries out digestion of food.

liver: a large, dark red organ that carries out many different functions, including production of bile and the regulation of blood glucose concentration.

pancreas: a creamy-white organ lying close to the stomach, which secretes pancreatic juice; it also secretes the hormones insulin and glucagon, which are involved in the control of blood glucose concentration.

absorbed: soaked up; nutrients are absorbed from the alimentary canal into the blood, through the walls of the small intestine.

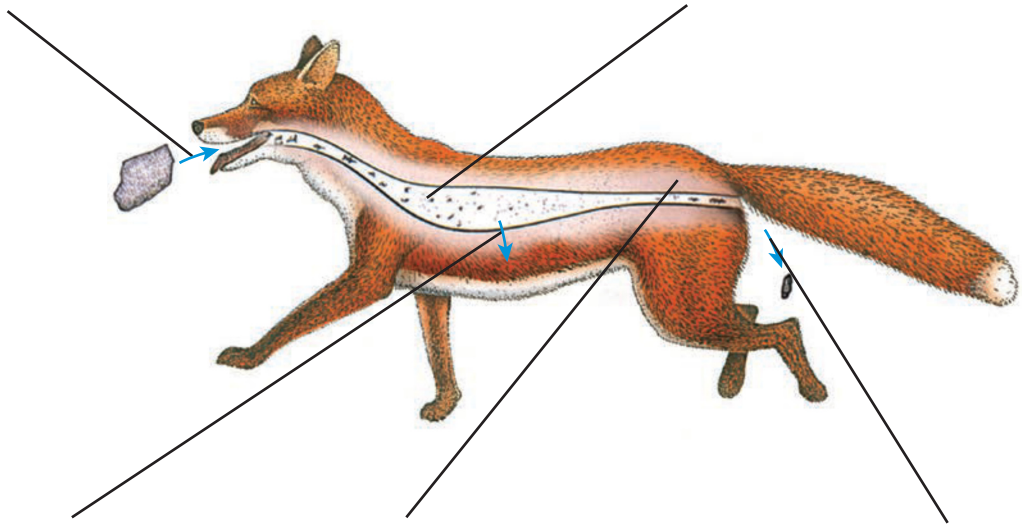
ingestion: the taking of food and drink into the body.

assimilation: the uptake and use of nutrients by cells.

chemical digestion: the breakdown of large molecules in food into smaller molecules, so that they can be absorbed.

1 Ingestion: This means taking food and drink into the mouth. We do this using the lips, teeth and tongue.

2 Digestion: The food that we eat contains large pieces and large molecules. The large pieces have to be broken down to small pieces (mechanical digestion) and the large molecules must be broken down to small molecules (chemical digestion). The small molecules can then get through the walls of the intestines and into the blood.



3 Absorption: This is the movement of the small nutrient molecules and mineral ions through the walls of the intestines and into the blood.

4 Assimilation: This is what happens to the nutrients as they become part of the body. They are absorbed by individual cells and used for energy or to make new substances.

5 Egestion: There is always some material in our food that we cannot digest. Much of this is fibre. This is not absorbed. It remains in the intestines and eventually passes out as faeces.

Figure B6.07: How the digestive system of a fox deals with food. The human digestive system works in a similar way.

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The alimentary canal

The alimentary canal is a long tube which runs from the mouth to the anus.

It is part of the digestive system. As we have seen, the digestive system also includes the liver and the pancreas.

The wall of the alimentary canal contains muscles, which contract and relax to make food move along. These muscular contractions are called peristalsis.

Sometimes, it is necessary to keep the food in one part of the alimentary canal for a while, before it is allowed to move to the next part. Special muscles can close the tube completely in certain places. They are called **sphincter muscles**.

To help the food to slide easily through the alimentary canal, it is **lubricated** with **mucus**. Mucus is made in **goblet cells** which are found in the lining of the alimentary canal, along its entire length.

Each section of the alimentary canal has its own part to play in the digestion, **absorption** and **egestion** of food. Figure B6.08 shows the main organs of the digestive system.

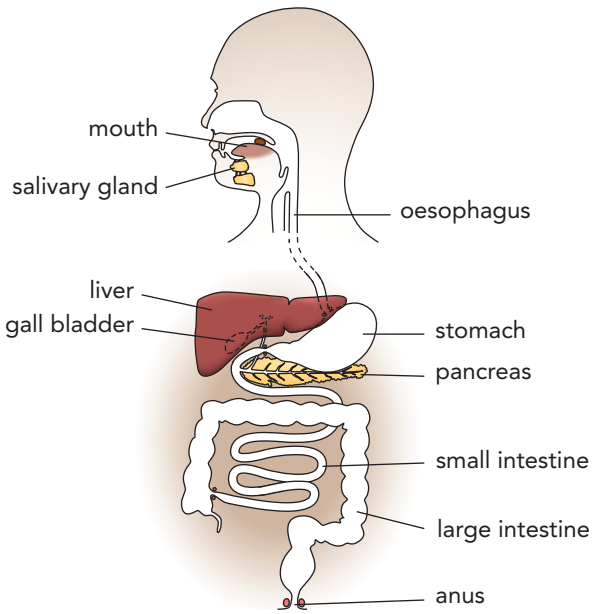

Figure B6.08: The human digestive system.

Questions

These questions are about Figure B6.08.

B6.02 Explain the difference between the alimentary canal and the digestive system.

B6.03 Name *two* parts of the digestive system that food does *not* pass through.

KEY WORDS

sphincter muscles: rings of muscle that can contract to close a tube.

lubricated: made smooth and slippery, to reduce friction.

mucus: a smooth, viscous fluid secreted by many different organs in the body.

goblet cells: cells found in the lining (epithelium) of the respiratory passages and digestive system, which secrete mucus.

absorption: the movement of nutrients from the alimentary canal into the blood.

egestion: the removal of undigested food from the body as faeces.

The mouth and salivary glands

Food is ingested using the teeth, lips and tongue. The teeth then bite or grind the food into smaller pieces. This increases the surface area of the food and begins physical digestion.

The tongue mixes the food with saliva and forms it into a little ball that can be swallowed.

The **salivary glands** make saliva. This is a mixture of water, mucus and the enzyme amylase. The water helps to dissolve substances in the food, allowing us to taste them. The mucus helps the chewed food to bind together to form a small ball, and lubricates it so that it slides easily down the oesophagus when it is swallowed. Amylase begins to digest starch. (See Topic B6.03 for much more about this, and all the other examples of digestion mentioned here.)

The oesophagus

There are two tubes leading down from the back of the mouth. The one in front is the **trachea** or windpipe, which takes air down to the lungs. Behind the trachea is the oesophagus, which takes food down to the stomach.

The 'hole' in the centre of the oesophagus, down which food can pass, is called a **lumen**. This word is used to describe the space in the middle of any tube in the body. There is a

KEY WORDS

salivary glands: groups of cells close to the mouth, which secrete saliva into the salivary ducts.

trachea: the tube through which air travels to the lungs; it has rings of cartilage in its walls, to support it.

lumen: the space in the centre of a tube, through which substances can move.

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lumen in all parts of the alimentary canal. All blood vessels also have a lumen.

The entrance to the stomach from the oesophagus is closed by a sphincter muscle. The muscle relaxes to let food pass into the stomach, then contracts to close the entrance again.

The stomach

The stomach (Figure B6.08) has strong, muscular walls. The muscles contract and relax to mix the food with the enzymes and mucus.

Like all parts of the alimentary canal, the stomach wall contains goblet cells which secrete mucus. It also contains cells which produce enzymes and others which make hydrochloric acid. The enzymes produced in the stomach digest proteins, so they are proteases.

The hydrochloric acid produces a low pH, of about pH 2, in the stomach, which kills harmful microorganisms in the food. This pH is also the optimum pH for the protease enzymes that act in the stomach.

The stomach can store food for quite a long time. After one or two hours, the sphincter at the bottom of the stomach opens and lets the partly digested food move into the **duodenum**.

The small intestine

The **small intestine** is the part of the alimentary canal between the stomach and the colon. It is about 5 metres long. It is called the small intestine because it is quite narrow. Different parts of the small intestine have different names. The first part, nearest to the stomach, is the duodenum. The last part, nearest to the colon, is the **ileum**.

The pancreas is a cream-coloured gland, lying just underneath the stomach. A tube called the **pancreatic duct** leads from the pancreas into the duodenum.

Pancreatic juice is a fluid made by the pancreas. It flows along the pancreatic duct into the duodenum. Pancreatic juice contains many different enzymes, so chemical digestion continues in the duodenum.

The ileum is where all the digested nutrients are absorbed into the blood. This is described in Topic B6.03. Water is also absorbed into the blood at this stage.

The large intestine and anus

The final part of the alimentary canal is the **large intestine**. It is made up of the **colon** and **rectum**. The colon absorbs much of the water that still remains in the food. The rectum stores undigested food as faeces. These are then egested from the body through the anus. Some of the organs of the digestive system are shown in Figure B6.09.

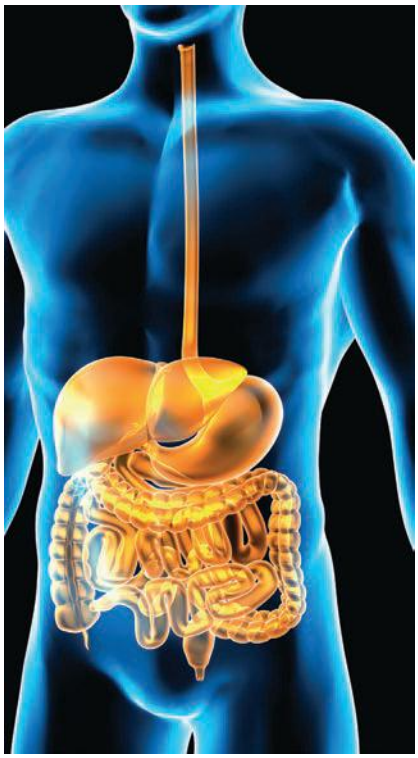

Figure B6.09: This artwork shows where some of the organs of the digestive system are positioned in the body. Can you name any of them?

The pancreas and liver

The pancreas and liver are important organs in the digestive system, but they are not part of the alimentary canal. Food does not pass through them.

KEY WORDS

duodenum: the first part of the small intestine, into which the pancreatic duct and bile duct empty fluids.

small intestine: a long, narrow part of the alimentary canal, consisting of the duodenum and ileum.

ileum: the second part of the small intestine; most absorption takes place here.

pancreatic duct: the tube that carries pancreatic fluid from the pancreas to the duodenum.

large intestine: a relatively wide part of the alimentary canal, consisting of the colon and rectum.

colon: the first part of the large intestine.

rectum: the second part of the large intestine, where faeces are produced and stored.

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We have seen that the pancreas secretes a fluid containing enzymes, which help with digestion of food in the duodenum. The liver also secretes a fluid that helps with digestion.

The gall bladder

The fluid secreted by the liver that helps with digestion is called **bile**.

The bile that has been made by the liver is stored in the **gall bladder**. When food enters the duodenum, the bile flows along the **bile duct** and is mixed with the food in the duodenum.

Bile is a yellowish green, alkaline, watery liquid, which helps to neutralise the acidic mixture from the stomach. This provides a suitable pH for enzyme action (see the topic Enzymes (Topic B6.03)).

Bile has another important function. Fats and oils are insoluble in water, so any fat or oil in the food that you eat stays as little drops that do not fully mix into the watery fluids inside the digestive system. Bile acts rather like liquid detergent. It breaks up large drops of fat or oil into tiny droplets, which can disperse among the watery liquids. A mixture of tiny, floating droplets of one liquid in another is called an emulsion. So, bile **emulsifies** fats.

KEY WORDS

bile: an alkaline fluid produced by the liver, which helps with fat digestion.

gall bladder: a small organ that stores bile, before the bile is released into the duodenum.

bile duct: the tube that carries bile from the gall bladder to the duodenum.

emulsifies: breaks down large drops of fat or oil into smaller droplets, increasing their surface area and allowing them to mix with watery liquids.

Questions

B6.04 List, in order, all the parts of the digestive system through which food pass as it moves from the mouth to the anus.

B6.05
- **a** Which of the parts you have named in Question B6.04 are involved in ingestion?
- **b** Which parts are involved in digestion?
- **c** Which parts are involved in absorption?
- **d** Which parts are involved in egestion?

B6.03 Digestion

The food that we eat usually contains large molecules of starch (a type of carbohydrate), protein and fat. These large molecules are too big to pass through the walls of the intestines and into the blood. They must be broken down into much smaller molecules, allowing them to be absorbed. As you have seen, this process is called digestion.

Table B6.03 summarises what happens to each of the large molecules of starch, protein and fat as a result of digestion. The molecules of vitamins and water are already small enough to be absorbed, and this is also the case for mineral ions. So, none of those need to be chemically digested.

Large molecule	Enzyme that breaks it down	Small molecules produced
starch	amylase	simple reducing sugars
protein	protease	amino acids
fat	lipase	fatty acids and glycerol

Table B6.03: The effect of digestion on starch, protein and fat.

Physical and chemical digestion

Digestion takes place in two stages: physical digestion and chemical digestion.

Physical digestion

Large pieces of food are broken down into smaller pieces. This is mostly done by the teeth, but the churning movements of the stomach also help. This physical digestion does not change the chemical components of the food in any way.

Chemical digestion

After physical digestion, the large molecules in the food are broken apart into smaller molecules. This involves chemical reactions. These reactions are catalysed by enzymes.

These smaller molecules are soluble in water, which makes it easier for them to be absorbed into cells.

The actions of the teeth and stomach help to break food into smaller pieces, increasing its surface area. This means enzymes can more easily make contact with the molecules in the food and start to break them apart.

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Enzymes

Table B6.04 summarises where each type of enzyme is made, and where it works in the human digestive system.

Enzyme	Where it is secreted	Where it acts	Function
amylase	by the salivary glands	in the mouth	breaks down starch to simpler sugars
	by the pancreas	in the duodenum	
protease	by the walls of the stomach	in the stomach	breaks down protein to amino acids
	by the pancreas	in the duodenum	
lipase	by the pancreas	in the duodenum	breaks down fats to fatty acids and glycerol

Table B6.04: The sites of secretion and action of digestive enzymes.

In Chapter B4, we saw that enzymes are affected by temperature and pH. The digestive enzymes in the human digestive system all work best at a temperature of about 38 °C, which is our normal body temperature.

The digestive enzymes vary in the pH at which they work best. The stomach walls secrete hydrochloric acid to kill bacteria, so the protease that works in the stomach has to be able to work in these conditions. It has an optimum pH of about 2. The enzymes that work in the duodenum require a pH of just above 6 to work at their fastest. This higher pH is provided by bile and pancreatic juice, which contain alkaline substances. These neutralise the acidic mixture that passes into the duodenum from the stomach.

Questions

B6.06 State *two* places in the human digestive system where starch is broken down to simple reducing sugars.

B6.07 State *two* places in the human digestive system where proteins are digested.

B6.08
- **a** From which part of the digestive system is lipase secreted?
- **b** In which part of the digestive system does lipase act?

B6.09 Bile emulsifies fats. Explain what this means, and why it is an important part of fat digestion.

ACTIVITY B6.02

Functions of organs in the digestive system

You can work in a group of two or three for this activity.

On a large sheet of paper, make a very big drawing of the human digestive system.

Leave plenty of space around your drawing, for labels and annotations.

Label each part. To each label, add a description of what happens in that part.

You could use different pens to colour code your written descriptions. For example, you could use one colour to represent physical digestion and a different colour to represent chemical digestion. You could also include a third colour to show the path of molecules into the blood by absorption.

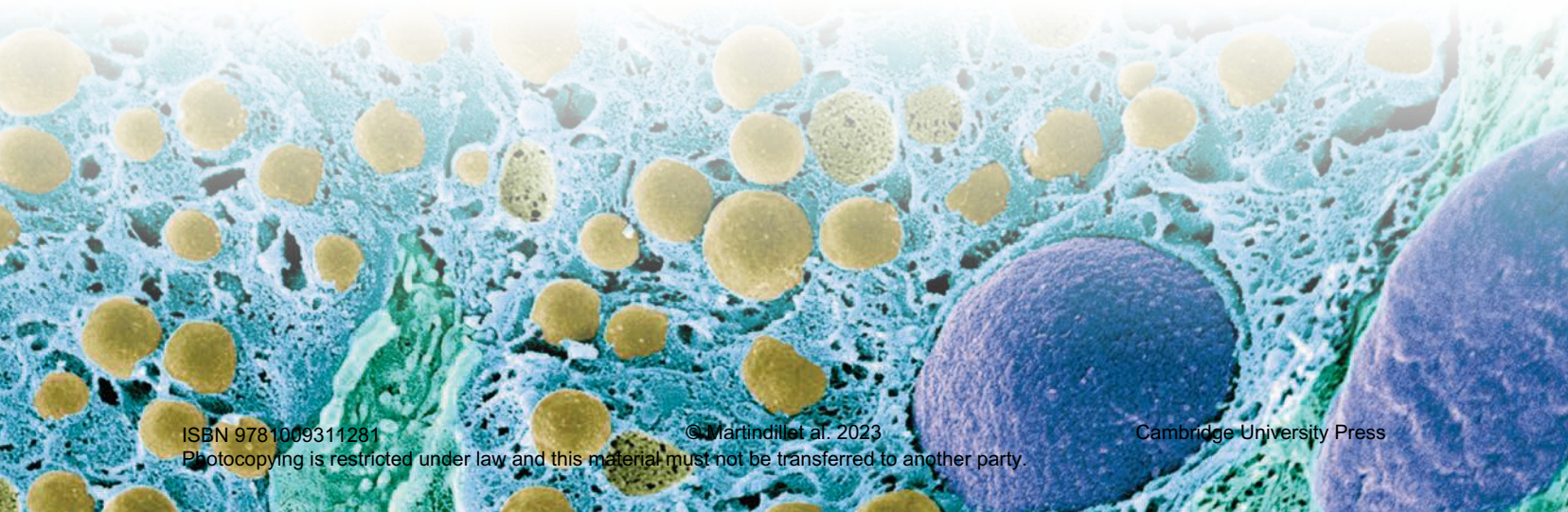
Note: After you have learnt about absorption, in the next topic in this chapter, you may like to return to your drawing and add some more information about the small intestine. So, try to leave a little bit of space for this.

Peer assessment

Exchange your finished drawing with another group.

Compare your drawing with theirs. Which one is clearer?

Which contains more information?
Which is the more interesting?



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PROJECT B6.01 MAKE A MODEL OF THE HUMAN ALIMENTARY CANAL

You are going to work in a group to make a model of the human digestive system.

You can use whatever materials you can find. For example, you may like to use cardboard tubes of various sizes, or balloons – whatever you think will work well for you. Be imaginative!

First, discuss in your group how you will construct your model. Think about the materials that you will need.

Gather your materials together and make your model. You will almost certainly make some changes to your original plan as you work – that is fine.

When everyone has completed their models, they can be displayed around the room. One or two people from each group should stay with their model and explain it to others as they walk around the display. Then swap over, so that everyone has a chance to see all the other models, and to help to explain their own model.

Figure B6.10: Students planning how to model the human digestive system.

SUMMARY

A balanced diet contains some of all six nutrient groups – proteins, carbohydrates, fats, minerals, vitamins and water – in suitable amounts and proportions. It also contains fibre.
Scurvy is caused by a lack of vitamin C, and rickets by a lack of vitamin D.
The digestive system is made up of the alimentary canal (the mouth, oesophagus, stomach, duodenum and ileum (small intestine), colon and rectum (large intestine)), the liver, gall bladder, salivary glands, and pancreas.
Food is first ingested. This is followed by digestion, absorption and assimilation. Food that cannot be absorbed is egested.
Physical digestion is done by the teeth and stomach. It involves breaking down food into smaller pieces without chemical change to the food molecules. It increases the surface area of food for the action of enzymes in chemical digestion.
Chemical digestion is done by enzymes in the mouth, stomach and small intestine. It involves breaking down large molecules of nutrients to small ones, so that they can be absorbed.
In chemical digestion: amylase breaks down starch to simpler reducing sugars; protease breaks down proteins to amino acids; lipase breaks down fats to fatty acids and glycerol.
Hydrochloric acid in the stomach provides a low pH for enzymes to work, and also kills harmful microorganisms in food.
Bile is secreted by the liver and stored in the gall bladder before being released into the duodenum. It emulsifies fats, which makes it easier for lipase to digest them.
Nutrients, including water, are absorbed into the blood from the small intestine. More water is absorbed from the colon.

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PRACTICE QUESTIONS

1 **Identify** the correct definition of the term assimilation.

A the breakdown of large molecules into small molecules

B the movement of small molecules from the intestine into the blood

C the movement of small molecules into cells, where they are used

D the taking of food into the mouth **[1]**

2 Identify a function of bile.

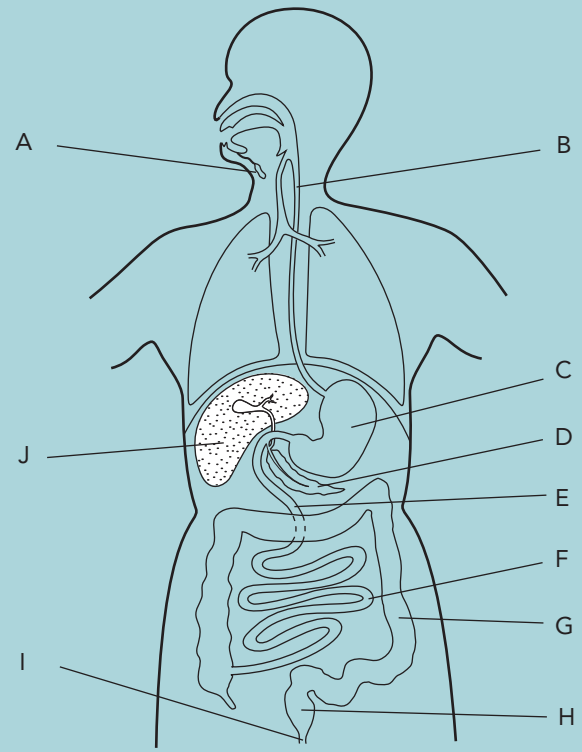
A chemically digesting fats

B emulsifying proteins

C killing harmful microorganisms

D increasing pH **[1]**

3 The diagram shows the human digestive system.



a Identify the parts labelled G and J. **[2]**

b **Give** the letters of *two* parts where amylase is secreted. **[2]**

c Give the letter of *one* part where lipase acts. **[1]**

d **Describe** how part C helps in digestion. **[6]**

[Total: 11]

COMMAND WORD

identify: name/select/recognise.

COMMAND WORDS

give: produce an answer from a given source or recall/memory.

describe: state the points of a topic/give characteristics and main features.

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SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
explain what is meant by a balanced diet	B6.01			
give examples of good sources of each type of nutrient, and the importance of each nutrient	B6.01			
identify the main organs of the digestive system	B6.02			
describe the functions of each of the organs in the digestive system	B6.02			
explain the difference between physical digestion and chemical digestion	B6.03			
explain why digestion has to happen before nutrients can be absorbed	B6.03			
state where amylase, protease and lipase act, and what they do	B6.03			
describe the function of hydrochloric acid in the stomach	B6.03			
explain the functions of bile, including providing an alkaline pH and emulsifying fats.	B6.03			

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B7 Transport

All learners study some content in this chapter

IN THIS CHAPTER YOU WILL:

- learn about the functions of xylem and phloem, and where they are found
- investigate the movement of water through stem and leaves
- learn about how the surface area of root hairs increases water uptake and mineral irons
- find out what transpiration is, why it happens, and conditions that affect its rate
- learn about translocation of sucrose and amino acids in plants
- find out about the circulatory system in animals
- learn about the structure and function of the heart
- learn about factors that increase the risk of developing heart disease
- investigate how exercise affects heart rate
- compare the structure and function of arteries, veins and capillaries
- find out about the components of blood, and what they do
- identify red and white blood cells in photomicrographs and diagrams
- identify lymphocytes and phagocytes in photomicrographs and diagrams
- explain how the structures of arteries and veins are related to their functions
- explain how the structures of capillaries are related to their functions.

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BEFORE YOU START

- Draw two very simple diagrams of a plant cell and a human (animal) cell, showing their structures.
- Draw arrows pointing into the cells, and label them to show what the cells need to take in to stay alive.
- Draw arrows pointing out of the cells, and label them to show what the cells have to get rid of.
- Think about how these substances are brought to the cells and taken away from them.
- Share your ideas with the rest of the class.

SCIENCE IN CONTEXT B7.01

The world's tallest trees

Is there any limit to the height to which a tree can grow? The world's tallest trees are the coastal redwoods, *Sequoia sempervirens*. They can be found in some parts of California in the USA. The tallest one is 116 m tall, growing in the Redwood National Park. This tree is probably 2500 years old.

Scientists think that it is impossible for a tree to grow taller than about 130 m. This is because the xylem that makes up most of a tree's trunk would not be able to transport water any higher than this.

Xylem is the tissue that wood is made of. It contains dead, empty cells joined end to end, called xylem vessels. These long tubes run all the way up through a tree's trunk and out into its branches. These vessels have two functions: they help to hold the tree up, and they provide a pathway for water to flow from the roots all the way up to the leaves at the top of the tree.

Discussion question

1 Small plants, such as mosses, do not have xylem vessels to transport water. How might water get to all the different cells of a moss plant?

Figure B7.01: Resistance to fire has allowed redwood trees to live for thousands of years.

B7.01 Transport in plants

Xylem and phloem

All organisms need to obtain substances from their environment. For plants, these substances are carbon dioxide and water for photosynthesis, and mineral ions which they absorb from the ground.

Plants have branching shapes. This gives them a large surface area in relation to their volume. It means that most cells are close to the surface. As we saw in Chapter B5, leaves are adapted to ensure that no cell is far away from the air. So, carbon dioxide can simply diffuse in through the **stomata** and air spaces, easily reaching the photosynthesising mesophyll cells.

Water comes from further away. Plants absorb water through their roots, and this water must be transported up to the leaves. The transport system that does this is made up of a tissue called **xylem**. Mineral ions are also transported in the xylem.

KEY WORDS

stomata: (singular: stoma) openings in the surface of a leaf, most commonly in the lower surface; they are surrounded by pairs of guard cells, which control whether the stomata are open or closed.

xylem: a plant tissue made up of dead, empty cells joined end to end; it transports water and mineral ions and helps to support the plant.

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Plants also have a second transport system, made up of a tissue called **phloem**. Phloem transports sucrose and amino acids from the leaves where they are made, to other parts of the plant such as its roots and flowers.

KEY WORD

phloem: a plant tissue made up of living cells joined end to end; it transports substances made by the plant, such as sucrose and amino acids.

ACTIVITY B7.01

Identifying the positions of xylem vessels in stems, roots and leaves

You are going to use micrographs (photographs taken using microscopes) to make simple diagrams. Your diagrams will show the position of xylem vessels in a stem, a root and a leaf.

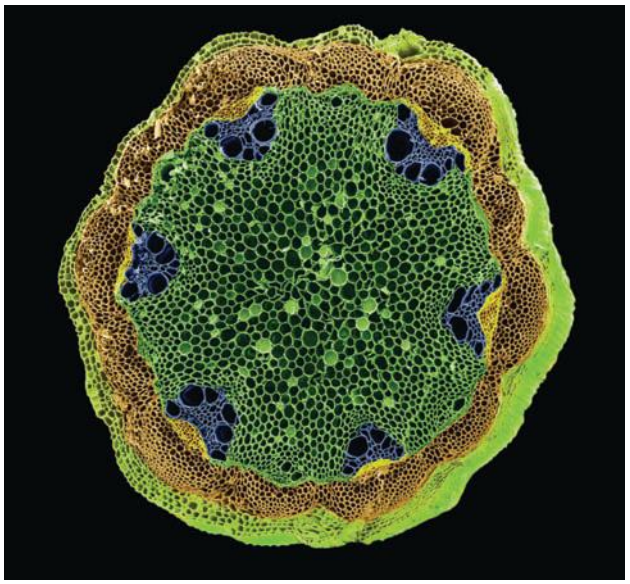

Figure B7.02: Scanning electron micrograph of a section across a plant stem.

1 Look at Figure B7.02. It shows a plant stem, cut across. The xylem vessels have been coloured blue.

2 Draw a circle (not a perfect one) to represent the section across the stem. Then draw triangles (not perfect ones) to show where the xylem vessels are found. Label the xylem on your drawing.

3 Look at Figure B7.03. It shows a plant root, cut across. The xylem vessels are the big, empty cells with red walls in the centre. The walls are red because a red stain has been used to make a carbohydrate in the xylem show up clearly.

4 Draw a diagram, similar to the one that you drew of the stem, to show the position of xylem vessels in a root.

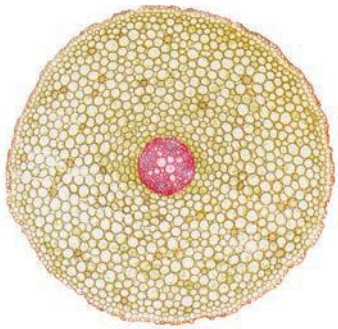

Figure B7.03: Photomicrograph of a section across a plant root.

5 Look at Figure B7.04. It shows part of a plant leaf, cut across. A stain has been used to colour the cell walls. The xylem vessels are the empty cells with purple walls, arranged in a semi-circle.

6 Draw a diagram, similar to the ones that you drew of the stem and root, to show the position of xylem vessels in a leaf.

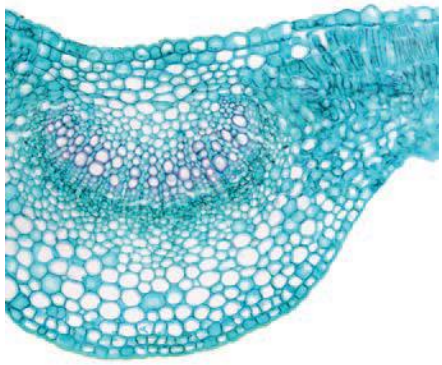

Figure B7.04: Photomicrograph of a section across a plant leaf.

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CONTINUED

Self assessment

How well did you achieve each of these goals?

Rate yourself according to the following scheme for each of the features of your drawing listed opposite.

☺ if you did it really well

😐 if you made a good attempt at it and partly succeeded

☹ if you did not try to do it, or did not succeed

- Your drawings are large – bigger than the size of the micrographs.
- You used a sharp pencil for your drawings.
- The lines in your drawings are single and unbroken.
- You showed the position of the xylem correctly and clearly.
- You labelled the xylem with a label line drawn with a ruler, touching the xylem.

Vascular bundles

Xylem vessels and phloem tubes are usually found close together. A group of xylem vessels and phloem tubes is called a vascular bundle.

The positions of vascular bundles in roots and stems are shown in Figures B7.05 and B7.06. In a root, vascular tissue is found at the centre. In a stem, vascular bundles are arranged in a ring near the outside edge. As you saw in Chapter B5, vascular bundles are also found in leaves. They help to support the leaves, holding them out flat to capture sunlight.

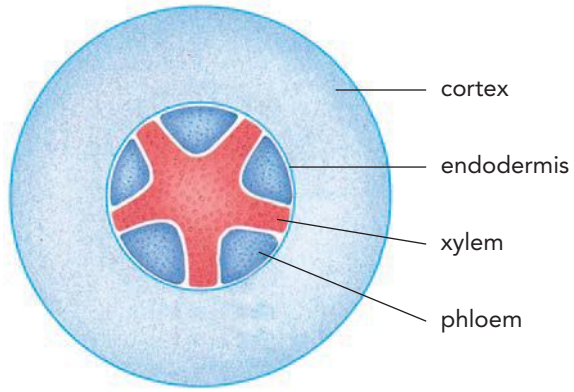

Figure B7.05: Diagram of a transverse section of a root.

Questions

B7.01 State the *two* functions of xylem.

B7.02 State the function of phloem.

B7.03 Use your diagrams from Activity 7.1 to describe in words the positions of xylem and phloem in roots, stems and leaves.

Water uptake

Plants take in water from the soil, through their root hairs. Figure B7.07 shows the end of a root, magnified.

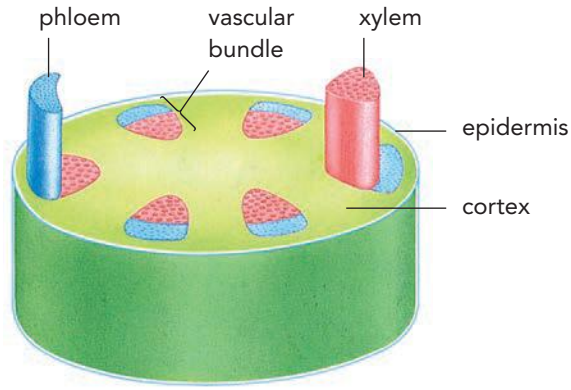

Figure B7.06: Diagram of a stem cut across, to show the positions of xylem and phloem tissue.

At the very tip is a protective cap, to protect the root as it grows through the soil. The rest of the root is covered by a layer of cells called the epidermis. The root hairs are formed from some of the cells in the epidermis.

You can see in Figure B7.07 that there are no root hairs at the very tip of the root – they start a little way behind it. Each root hair is a long epidermal cell (see Figures B7.08 and B7.09). Root hairs do not live for very long. As the root grows, the hairs get damaged by the soil particles.

The main function of root hairs is to absorb water from the soil. We have seen that water moves into a root hair by osmosis. The cytoplasm and cell sap inside the root hair are quite concentrated solutions. The water in the soil is normally a more dilute solution. So, water diffuses into the root hair, down its concentration gradient, through the partially permeable cell surface membrane.

The long, thin root hairs have a large surface area, which increases the uptake of water.

Their large surface area also increases the rate of absorption of mineral ions.

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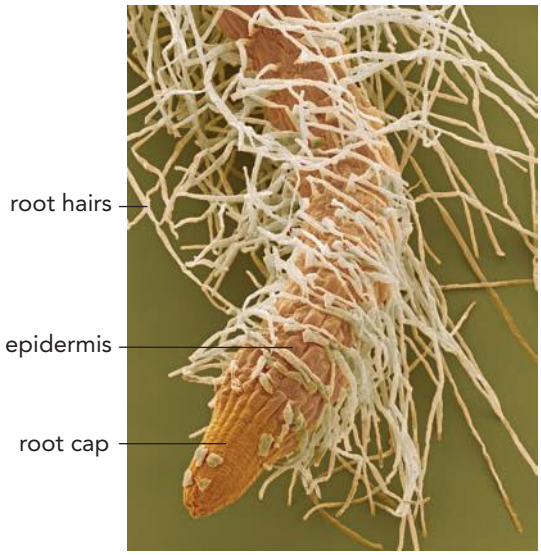

Figure B7.07: A micrograph of the tip of a root, magnified 70 times.

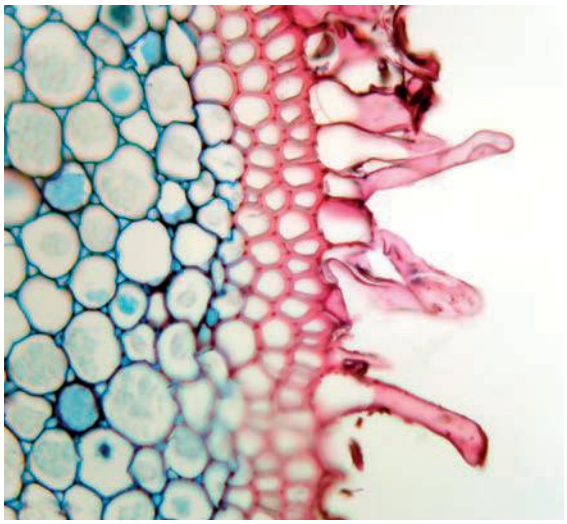

Figure B7.08: A photomicrograph showing part of a transverse section of a root (×100). You can see several root hairs on the right-hand side.

The pathway of water through a plant

The root hairs are on the edge of the root. The xylem vessels are in the centre. Before the water can be taken to the rest of the plant, it must travel across the root to the xylem vessels.

The path that the water takes is shown in Figure B7.09. The water travels by osmosis through the cortex, from cell to cell. Some of it may also just seep through the spaces between the cells, or through the cell walls, never actually entering a cell at all. Eventually it reaches the xylem vessels in the middle of the root. These transport it all the way up through the stem and into the leaves.

When water reaches the xylem, it moves up xylem vessels in the same way that a drink moves up a straw when you suck it. When you suck a straw, you reduce the pressure at the top of the straw. The liquid at the bottom of the straw is at a higher pressure, so the liquid flows up the straw into your mouth.

The same thing happens with the water in xylem vessels. The pressure at the top of the vessels is lowered, while the pressure at the bottom stays high. Water therefore flows up the xylem vessels.

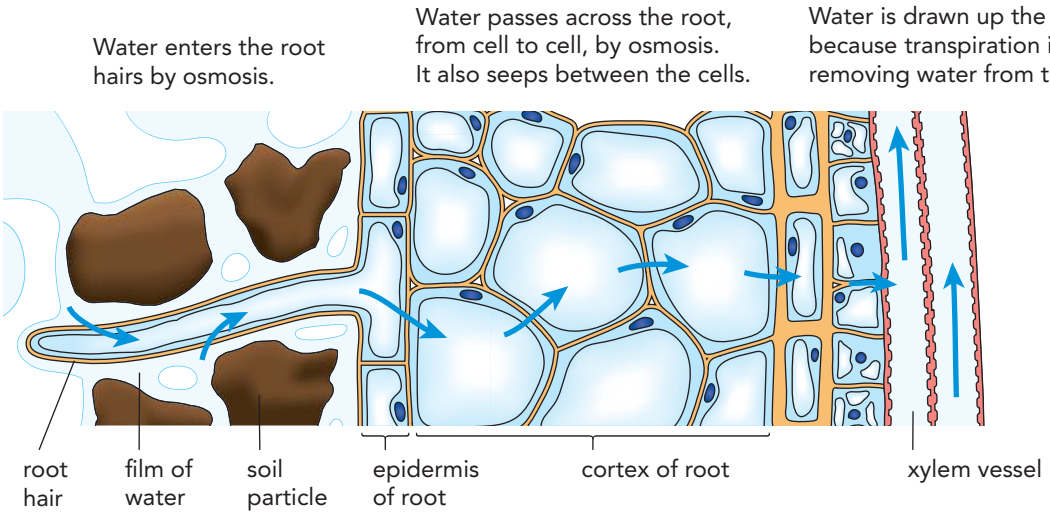

Figure B7.09: How water moves from the soil to the xylem vessels in a root.

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Questions

B7.04 What are the functions of root hairs?

B7.05 Explain how the structure of a root hair helps it to carry out its function.

B7.06 Use your knowledge of osmosis to explain how water moves from the soil into a root hair.

B7.07 Use your understanding of water potential to explain how water moves from the soil and across the root cortex.

Transpiration

Transpiration is the loss of water vapour from a plant. Most of this loss takes place from the leaves (Figure B7.10).

You may remember that there are openings on the surface of the leaf called stomata. There are usually more stomata on the underside of the leaf, in the lower epidermis. The mesophyll cells inside the leaf are each covered with a thin film of moisture. Some of this film of moisture evaporates from the cells into the air spaces. This water vapour diffuses out of the leaf through the stomata. Water from the xylem vessels in the leaf then travels to the mesophyll cells by osmosis to replace it.

Water is constantly being taken from the top of the xylem vessels, to supply the cells in the leaves. This reduces the effective pressure at the top of the xylem vessels, so that water flows up them. This process is known as the transpiration stream (Figure B7.10).

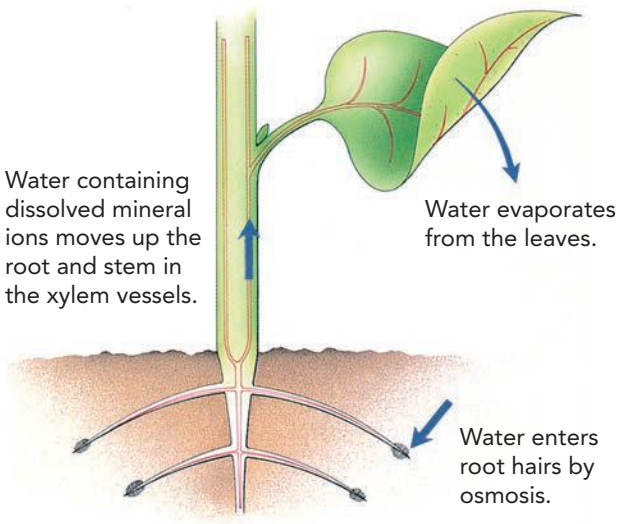

Figure B7.10: The transpiration stream.

KEY WORDS

transpiration: the loss of water vapour from leaves.

spongy mesophyll: the layer of cells immediately beneath the palisade mesophyll, where some photosynthesis happens; this tissue contains a lot of air spaces between the cells.

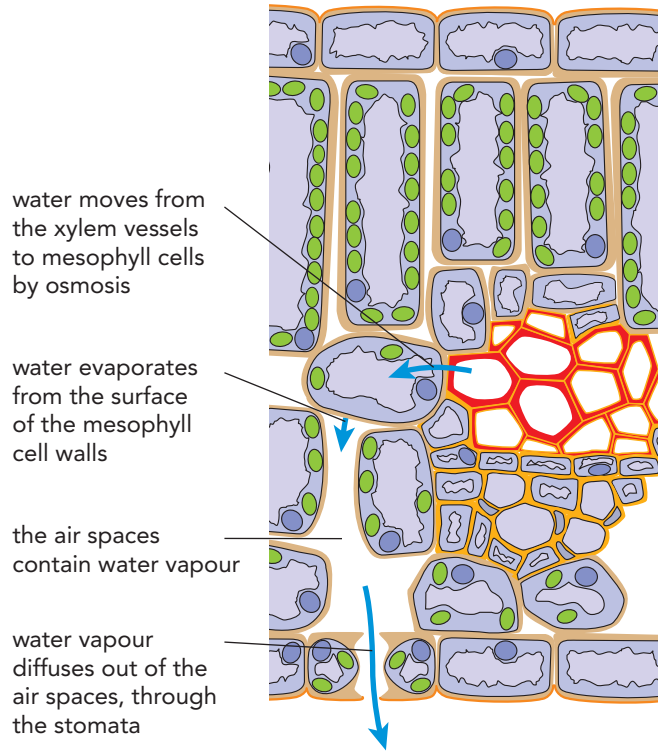

Figure B7.11: How water moves from xylem to the air, through a plant leaf.

The **spongy mesophyll** tissue in a plant leaf is very important in helping to keep water moving through the plant. The combined surface area of all the spongy mesophyll cells is very large, and this surface is in contact with the air spaces in the leaf. Liquid water moves into the mesophyll cells from the xylem vessels by osmosis. A lot of this water then evaporates from the cell walls, ending up as water vapour in the interconnecting air spaces (Figure B7.11).

As we have seen, the water vapour then diffuses out through the stomata and into the air surrounding the leaf. The rate at which this water vapour diffuses out of the leaf is generally greater in leaves where there are many open stomata.

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EXPERIMENTAL SKILLS B7.01

Investigating the pathway of water through the above-ground parts of a plant

In this investigation, you will use a coloured liquid to trace the path of water as it moves through a plant stalk and leaf. You will practise following instructions, observing carefully and drawing conclusions. You can also try planning another experiment using the technique you have just used.

You will need:

- a celery stalk, with some leaves attached
- a small beaker
- some water with a coloured dye added, such as eosin
- a sharp knife or scalpel
- a surface on which you can cut the stalk (for example, a white tile)
- a hand lens.

Safety

Take care with the sharp knife or scalpel. Try not to get the dye on your skin or clothes, as it will be very difficult to wash off.

Method

1 Put a small quantity of the coloured water into a beaker.

2 Stand the celery in the coloured water. Leave it for at least an hour – longer if you can.

3 Remove the celery from the water. Place it on a tile and cut it across. Study the cut end with a hand lens. It may look like the one in Figure B7.12.

4 Make a labelled drawing of the surface of your celery stalk.

5 Look at the leaves. Can you see the dye in the leaves? If so, describe which part contains the dye.

Questions

1 From the position of the coloured areas in the stalk in Figure B7.12, and in your own celery stalk, which tissue in the stalk do you think contains the coloured water?

2 Did the coloured water get into the leaves? If so, which part of the leaf contains the coloured water?

3 Suggest how you could use this technique to test this hypothesis:

Water moves more quickly through a plant when the temperature is higher.

Think about:

- the variable you will change and how you will do this
- the variables you will try to keep constant, and how you will do this
- how and when you will measure your results
- any safety risks in your experiment, and how you will minimise them.

Figure B7.12: A cut celery stalk that has been standing in a solution of a red dye.

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ACTIVITY B7.02

How can we use a balance to estimate rate of transpiration?

Figure B7.13 shows two plants in pots. One plant has a transparent plastic bag covering the whole plant and pot. The other plant has a transparent plastic bag covering only the soil and pot.

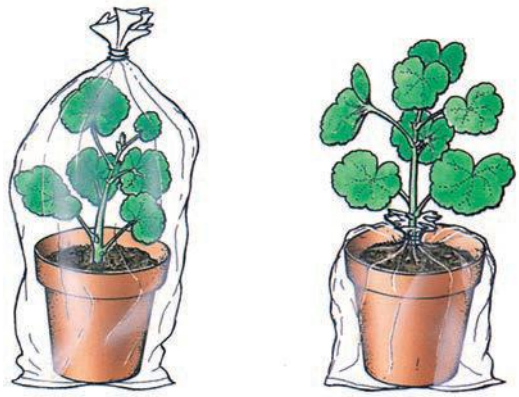

Figure B7.13: Using pot plants to measure the rate of transpiration.

In your group, discuss how you could use these plants and a balance (scale) to measure how quickly a plant is losing water vapour by transpiration.

Be ready to share your ideas with the rest of the class.

Questions

B7.08 Put these words in order, to describe the sequence in which water moves through a plant.

mesophyll cells

root cortex cells

root hair cells

xylem

B7.09 State whether water is in the form of a liquid or a gas, in each of these places:

a as it moves from the soil into root hairs

b as it moves through xylem vessels

c as it moves out of plant leaves into the air.

Conditions that affect transpiration rate

The rate at which water vapour diffuses out of a plant's leaves is affected by the environment. Transpiration happens faster when the temperature is high.

The higher the temperature, the greater the kinetic energy of water molecules. This means that water evaporates faster from the surface of the mesophyll cells, and the water vapour diffuses out of the leaf into the air more quickly.

Transpiration rate is also affected by **humidity**. Humidity means the moisture content of the air. The higher the humidity, the less water vapour will diffuse out from the leaves. This is because there is not much of a diffusion gradient for the water between the air spaces inside the leaf, and the wet air outside it. Transpiration decreases as humidity increases.

If the temperature is high, it is windy and the air is very dry, then transpiration will happen very quickly. The plant may lose water from its leaves faster than it can take it up from its roots. The individual cells in the plant lose so much water that they become flaccid. The tissues in the leaves are no longer supported by the turgid cells pushing outwards against one another. The leaves become soft and floppy. This is called **wilting** (Figure B7.14).

Figure B7.14: These pictures, taken over a period of one hour, show a plant that is gradually losing more water by transpiration than it can take up into its roots.

KEY WORDS

humidity: how much water vapour is present in air.

wilting (of a plant): losing more water than it can take up, so the cells lose their turgidity.

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EXPERIMENTAL SKILLS B7.02

Using a potometer

It is not easy to measure how much water is lost from the leaves of a plant. It is much easier to measure how fast the plant takes up water. The rate at which a plant takes up water depends on the rate of transpiration. The faster a plant transpires, the faster it takes up water.

Figure B7.15 illustrates apparatus which can be used to compare the rate of transpiration in different conditions.

It is called a potometer, which simply means 'water measurer'. By recording how fast the air/water meniscus moves along the capillary tube, you can compare how fast the plant takes up water in different conditions. A capillary tube is a glass tube with a very narrow hole.

There are many different kinds of potometer, so yours might not look like Figure B7.15. The simplest kind is just a long glass tube which you can fill with water. A piece of rubber tubing slid over one end allows you to fix the cut end of a shoot into it, making an airtight connection (Figure B7.16). This works just as well as the one in Figure B7.15 but is much harder to refill with water.

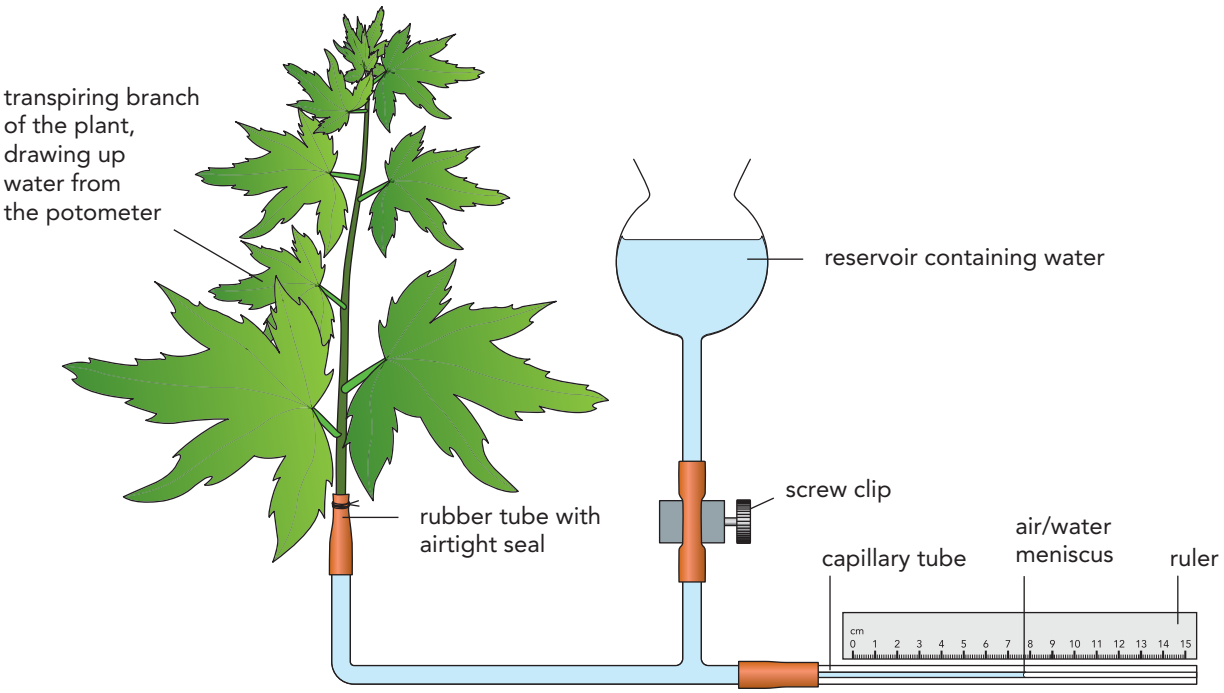

Figure B7.15: A potometer with a reservoir, which makes it easy to refill.

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CONTINUED: B7.02

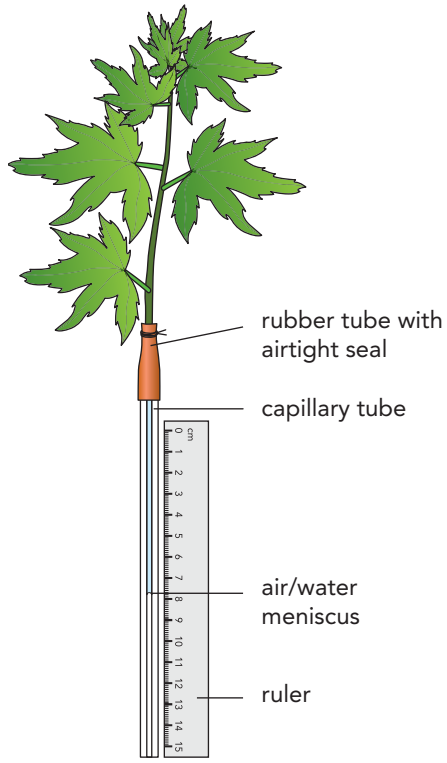

Figure B7.16: A simpler potometer without a reservoir. This one can be refilled by taking it apart and submerging the tube in water.

In this investigation, you will use a potometer to measure how fast a plant shoot takes up water in different conditions. You will practise handling apparatus carefully, making accurate measurements, recording results and drawing conclusions. You will also evaluate your method and think about possible improvements.

You will need:

- a potometer, like the ones in Figure B7.15 or B7.16
- a retort stand, boss and clamp to support the potometer
- a fresh, leafy shoot
- a sharp blade to cut the end of the shoot so that it fits into the potometer
- a timer
- a fan
- access to places with different temperatures – for example, a warm room and a fridge.

Safety

Take care with the sharp blade. In step 2, put the plant shoot onto a non-slip surface such as a cork board to cut it. Cut away from you, not towards you.

Before you start

Look carefully at your potometer and check you know how it works and how to use it.

Method

1. Fill the potometer with water. If you have a potometer like the one in Figure B7.15, you can simply open the clip and then close it once the tubes are all full of water. If your potometer is like the one in Figure B7.16, submerge it in a big container of water (such as a big sink).
2. Cut a plant shoot, making a slanting cut. Push the shoot into the potometer. If your potometer is like the one in Figure B7.16, do this while the tube is still completely under water.
3. If you have submerged your potometer in water, take it out of the water and stand it on the bench. Check that your potometer is airtight and that there are no air bubbles. (If you suspect it is not airtight, you can smear petroleum jelly over anywhere that you think might be leaking.)
4. Now leave the apparatus in a light, airy place. Fix the ruler close to the tube, to act as a scale. As the plant transpires, the water it loses is replaced by water taken up through the cut end of the stem. Air will be drawn in at the end of the capillary tube.
5. When the air/water meniscus reaches the scale, begin to record the position of the meniscus every two minutes for ten minutes.
6. Repeat the investigation, but with the apparatus in a different situation. You could try each of these:
   - blowing it with a fan
   - putting it in a refrigerator.

Questions

1. a Did you have any difficulties setting up the potometer and getting the meniscus to move? If so, explain what you think caused the difficulties.
   b Did you manage to overcome the difficulties? If so, describe how you did this.
2. Explain why the air/water meniscus moves along the scale.
3. Use your results to draw line graphs, so that you can easily compare the rate of movement in different conditions.

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Translocation

Leaves make carbohydrates by photosynthesis. They also use some of these carbohydrates to make amino acids, proteins, fats and oils and other organic substances.

Some of the substances made in the leaves, especially sucrose and amino acids, are transported to other parts of the plant in the phloem tubes. This is called **translocation**.

Sources and sinks

The part of a plant from which sucrose and amino acids are being translocated is called a **source**. The part of the plant to which they are being translocated is called a **sink**.

When a plant is actively photosynthesising and growing, the leaves are generally the major sources of translocated material. They are constantly producing sucrose, which is carried in the phloem to all other parts of the plant. These 'receiving' parts – the sinks – include the roots and flowers.

The roots may change some of the sucrose to starch and store it. The flowers use the sucrose to make fructose (an especially sweet-tasting sugar found in nectar). Later, when the fruits are developing, sucrose may be used to produce sweet, juicy fruits ready to attract animals.

But many plants have a time of year when they wait in a state of reduced activity for harsh conditions to end. In a hot climate, this may be during the hottest, driest season. In temperate countries, it may be during the winter.

During these difficult times, the plant does not photosynthesise. It survives by using its stores of starch, oils and other materials in its roots. The stored materials are converted to sucrose and transported to other parts of the plant. So, these storage areas have now become sources.

KEY WORDS

translocation: the movement of sucrose and amino acids in phloem from sources to sinks.

source: part of a plant that releases sucrose or amino acids, to be transported to other parts.

sink: part of a plant to which sucrose or amino acids are being transported, and where they are used or stored.

For example, baobab trees (Figure B7.17) grow in tropical countries such as Madagascar. In the wet season, their leaves photosynthesise and make sucrose. This is transported to the trunk and roots, where it is stored as starch. In the dry season, the baobab drops its leaves. When it rains again, the stores of starch are changed to sucrose, and transported to the growing buds, helping them to grow and form new leaves.

You can see from this example that phloem can transfer sucrose in either direction – up or down the plant. This is not true for the transport of water in the xylem vessels. Water can only go upwards, because transpiration always happens at the leaf surface, and it is this that provides the 'pull' to draw water up the plant.

Questions

B7.10 In the wet season, suggest which part of a baobab is a source, and which parts are sinks.

B7.11 As the dry season comes to an end, suggest which part of a baobab becomes a source, and which parts are sinks.

B7.12 Phloem tubes can transport sucrose both up and down a plant. Explain why xylem can only transport water up a plant and not down it.

Figure B7.17 a: Baobab trees in the wet season, when the leaves are sources of sucrose. **b:** In the dry season, the stems and roots store starch, ready to supply the leaves with sucrose when they begin to grow in a few months' time.

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B7.02 Transport in animals

Circulatory systems

The main transport system of all mammals, including humans, is the blood system. It is also known as the **circulatory system**. It is a network of tubes, called blood vessels. A pump, the heart, keeps blood flowing through the vessels.

Figure B7.18 shows the general layout of the human blood system. The arrows show the direction of blood flow. Put your finger on the position of the lungs, at the top of the diagram, and then follow the arrows. You can see that blood flows from the lungs into the left-hand side of the heart via the pulmonary vein, and then out to the rest of the body. It then flows back to the right-hand side of the heart, before travelling to the lungs again via the pulmonary artery.

The blood in the left-hand side of the heart has come from the lungs. It contains oxygen, which was picked up in the capillaries surrounding the alveoli. It is called **oxygenated blood**.

This oxygenated blood is then sent around the body. Some of the oxygen is taken up by the body cells, which need oxygen for respiration. When this happens, the blood becomes deoxygenated. The **deoxygenated blood** is brought back to the right-hand side of the heart. It then goes to the lungs, where it becomes oxygenated once more.

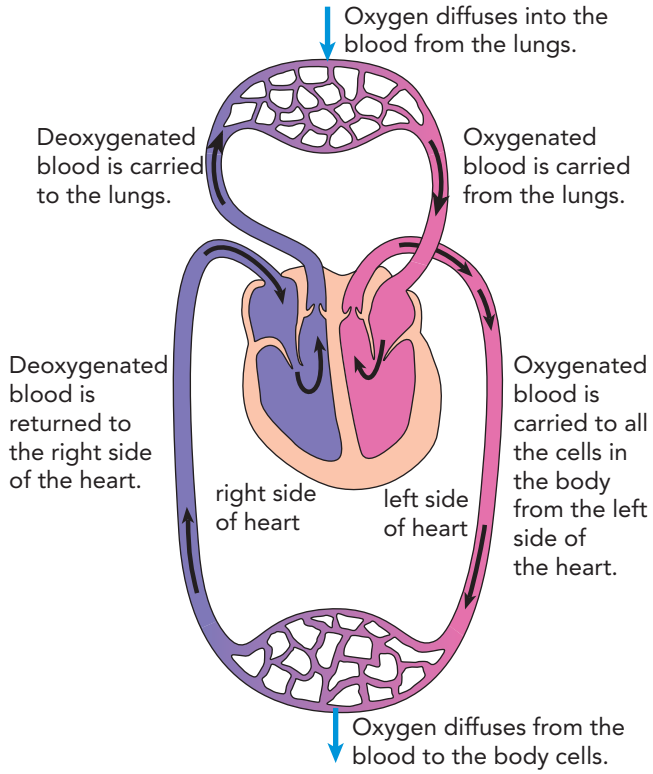

Figure B7.18: The general layout of the circulatory system of a human, as seen from the front.

Questions

B7.13 Look at Figure B7.18. Which side of the heart contains oxygenated blood, and which contains deoxygenated blood?

B7.14 Explain how, and where, blood becomes deoxygenated.

Double circulatory systems

The circulatory system shown in Figure B7.18 is a **double circulatory system**. This means that the blood passes through the heart twice on one complete circuit of the body.

We can think of the double circulatory system as being made up of two parts. The blood vessels that take the blood to the lungs and back are called the pulmonary system. The blood vessels that take the blood to the rest of the body and back are called the systemic system.

Double circulatory systems have some advantages over single circulatory systems. When blood flows through the tiny blood vessels in a fish's gills or a mammal's lungs, it loses a lot of the pressure that was given to it by the pumping of the heart. In a mammal, this low-pressure blood is delivered back to the heart, which raises its pressure again before sending it off to the rest of the body.

In a fish, the low-pressure blood just continues around the fish's body. This means that blood travels much more slowly to a fish's body organs than it does in a mammal.

This is particularly important when you think about the delivery of oxygen for respiration. Any tissues that are metabolically very active need a lot of oxygen delivered to them as quickly as possible, and this delivery is much more effective in a mammal than in a fish.

KEY WORDS

circulatory system: a system of blood vessels with a pump and valves to ensure one-way flow of blood.

oxygenated blood: blood containing a lot of oxygen.

deoxygenated blood: blood containing only a little oxygen.

double circulatory system: a system in which blood passes through the heart twice on one complete circuit of the body.

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Heart

The function of the heart is to pump blood around the body. It is made of a special type of muscle that contracts and relaxes regularly, throughout life.

Figure B7.19 is a section through a human heart. The heart is divided into four spaces, called chambers. The two upper chambers are called **atria** (singular: **atrium**). The two lower chambers are **ventricles**. The chambers on the left-hand side are completely separated from the ones on the right-hand side by a **septum**.

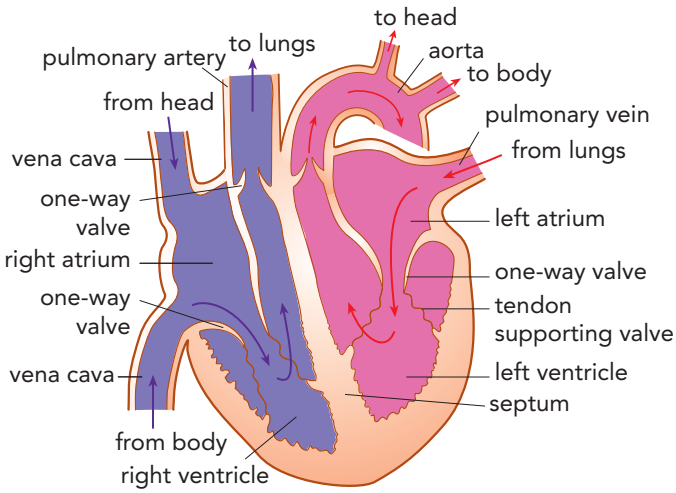

Figure B7.19: A vertical section through a human heart, seen from the front.

If you look at Figure B7.19, you will see that blood flows into the heart at the top, into the atria. Both of the atria receive blood.

From the atria, the blood flows into the ventricles. The muscles in the walls of the ventricles contract. This pumps the blood out of the heart. The muscle contracts strongly, producing a large force that squeezes inwards on the blood inside the heart and pushes it out.

Valves in the heart and blood vessels make sure the blood flows in the correct direction.

The left atrium receives blood from the lungs, via the **pulmonary veins.** The right atrium receives blood from the rest of the body, arriving through the big veins called the **venae cavae** (singular: **vena cava**).

The blood in the left ventricle is pumped into the **aorta**. This is a big artery that takes the blood around the body. The right ventricle pumps blood into the **pulmonary artery**, which takes it to the lungs.

Questions

B7.15 Look at Figure B7.18 and Figure B7.19. List, in order, the parts of the heart that blood flows through on one complete journey around the circulatory system.

B7.16 Which parts of the heart contain oxygenated blood?

B7.17 Do arteries carry blood towards or away from the heart?

B7.18 Do veins carry blood towards or away from the heart?

B7.19 Describe how blood is pushed out of the heart.

Coronary arteries

Figure B7.20 shows the external structure of a human heart. You can see that there are blood vessels on the outside of the heart. They are called the **coronary arteries**. These vessels supply blood to the heart muscles.

It may seem odd that this is necessary, when the heart is full of blood. However, the muscle of the heart is so thick that the nutrients and oxygen in the blood inside the heart would not be able to diffuse to all the muscle quickly enough. The heart muscle needs a constant supply of nutrients and oxygen, so that it can undergo aerobic respiration. This releases energy that the muscle uses to contract. The coronary arteries supply the nutrients and oxygen that the muscle needs.

KEY WORDS

atria (singular: **atrium**): the thin-walled chambers at the top of the heart, which receive blood.

ventricles: the thick-walled chambers at the base of the heart, which pump out blood.

septum: the structure that separates the left and right sides of the heart.

valves: structures that allow a liquid to flow in one direction only.

pulmonary veins: the veins that carry oxygenated blood from the lungs to the left atrium of the heart.

venae cavae (singular: **vena cava**): the large veins that bring deoxygenated blood to the right atrium.

aorta: the largest artery in the body, which receives oxygenated blood from the left ventricle and delivers it to the body organs.

pulmonary artery: the artery that carries deoxygenated blood from the right ventricle to the lungs.

coronary arteries: vessels that deliver oxygenated blood to the heart muscle.

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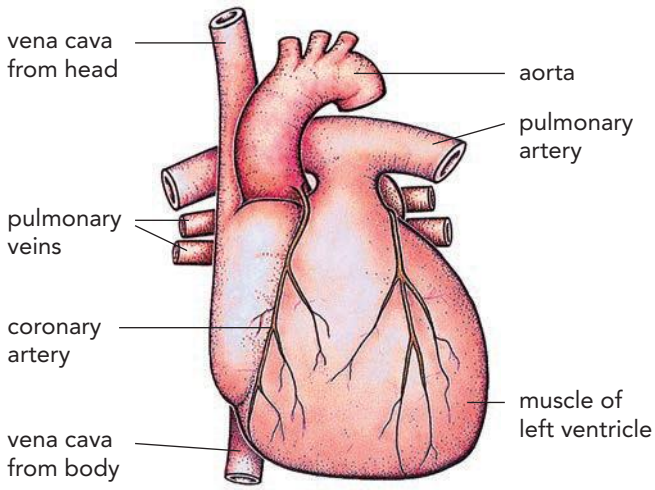


Figure B7.20: External appearance of a human heart.

Coronary heart disease

Coronary arteries can become blocked. In some people, cholesterol deposits build up inside the walls of arteries, including the coronary arteries (Figure B7.21). These deposits make the artery wall stiffer and the lumen narrower, so it is more difficult for blood to flow through. Blood clots can form. If the coronary artery is blocked, the cardiac muscle does not get any oxygen. The muscle cells cannot respire aerobically, so they cannot obtain energy to allow them to contract. The heart therefore stops beating.

Blockage of the coronary arteries is called **coronary heart disease (CHD)**. It is a very common cause of illness and death, especially in developed countries. We know several factors that increase a person's risk of getting CHD.

Preventing CHD

CHD is one of the commonest causes of death in many countries. No one can completely eliminate the risk of developing CHD, but there is a lot that can be done to reduce this risk.

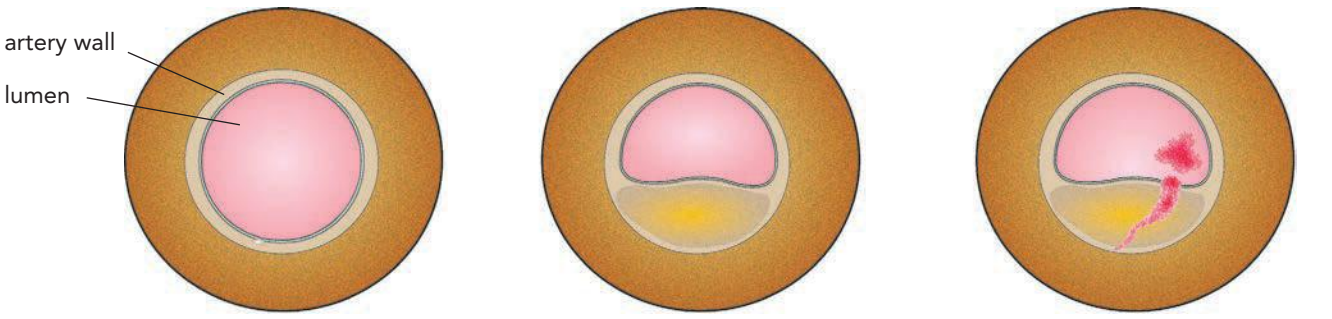
The most obvious thing you can do is not to smoke cigarettes. Smoking greatly increases the chances of developing CHD, as well as many other unpleasant and dangerous health problems.

Taking care over your diet is also a good thing to do. A diet that is high in saturated fats is linked with an increase in the concentration of cholesterol in a person's blood. This, in turn, increases the risk of CHD. Meat is higher in saturated fats than plant-based foods, so one simple way to reduce the risk of CHD is to substitute animal fats with plant oils when you are cooking. Fast foods are often high in animal fat, so these should be eaten in moderation.

Regular exercise has a very beneficial effect on many parts of the body, including the heart (Figure B7.22). Most people can find some kind of exercise that they enjoy. Exercise helps to keep you fit, prevents excessive weight gain and decreases blood pressure. It also has a 'feel-good' effect, by helping to clear your mind of things that may be worrying you and causing the release of chemicals in the brain that increase feelings of well-being.

KEY WORDS

coronary heart disease (CHD): disease caused by blockage of the coronary arteries.



1 This is a transverse section across a normal coronary artery.

2 Cholesterol deposits make the lumen of the artery narrower. This increases the blood pressure. It also makes the wall of the artery much stiffer.

3 Blood clots can form. If one breaks away, it may get stuck in a smaller blood vessel and stop the blood from getting through.

Figure B7.21: How coronary heart disease (CHD) is caused.

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Figure B7.22: Regular exercise can decrease the risk of developing CHD.

Heartbeat

You may be able to feel your heart beating if you put your hand on your chest. Most people's hearts beat about 60 to 75 times a minute when they are resting. If you put your head against a friend's chest or use a stethoscope, you can also hear the sounds of the valves closing with each heartbeat. They sound rather like 'lub-dub'. Each complete 'lub-dub' represents one heartbeat.

A good way to measure the rate of your heartbeat is to take your **pulse rate**. A pulse is the expansion and relaxation of an artery, caused by the heart pushing blood through it. Your pulse rate is therefore the same as your heart rate. You can find a pulse wherever there is an artery fairly near to the surface of the skin. Two good places are inside your wrist, and just to the side of the big tendons in your neck. There are also phone apps and smart watches that can automatically record your pulse rate.

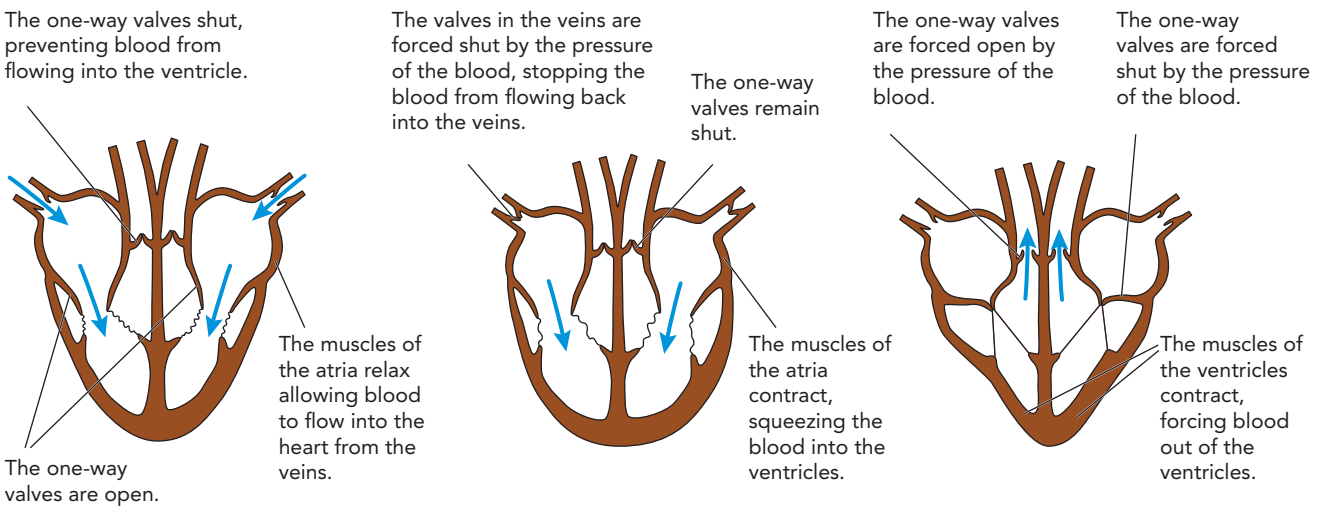
KEY WORDS

pulse rate: the number of times an artery expands and recoils in one minute; it is a measure of heart rate.

How the heart beats

The heart beats as the muscles in its walls contract and relax. When they contract, the heart becomes smaller, squeezing blood out (Figure B7.23). When they relax, the heart becomes larger, allowing blood to flow into the atria and ventricles.

We have seen that there is a one-way valve between the left atrium and the left ventricle, and another between the right atrium and ventricle. The valve on the left-hand side of the heart is made of two parts and is called the bicuspid valve or the mitral valve. The valve on the right-hand side has three parts and is called the tricuspid valve.



Muscles in the heart are relaxed. Blood flows into the heart.

Muscles in walls of atria contract. The muscles of the ventricles remain relaxed. Blood is forced from the atria into the ventricles.

Muscles in walls of ventricles contract. Blood is forced out of the ventricles into the arteries.

Figure B7.23: How the heart beats.

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As the walls of the atria contract, they increase the pressure of the blood in the atria. This pushes down on the one-way valves, swinging them open like doors and allowing blood to flow through, down into the ventricles. But when the ventricles contract, the valves are pushed closed again by the pressure of the blood in the ventricles. The tendons attached to them stop them from swinging up too far. They have to stop in the 'closed' position.

Questions

B7.20 Describe where you would find coronary arteries and explain their function.

B7.21 List *two* different ways you can measure your heart rate.

B7.22 Explain how the septum and valves help to ensure that fully oxygenated blood leaves the heart in the aorta at high pressure.

EXPERIMENTAL SKILLS B7.03

Investigating the effect of physical activity on heart rate

In this investigation, you will measure your pulse rate before and after exercise. You will practise measuring carefully, recording results clearly and using them to draw a line graph.

You will need:

- a timer, or a smart watch that can measure pulse rate.

Safety

If you are worried that doing exercise might make you ill, do not do it! You can measure someone else's pulse rate instead.

Before you start

Practise measuring pulse rate. Try placing two fingers on your own neck. Rest them gently close to one of the big tendons and try to feel the beating of your pulse (Figure B7.24). When you are confident that you can feel the pulse, try to find it on your partner's neck. If you are going to use a smart watch to measure pulse rate, make sure that you know how to use it.

Now practise counting how many pulses there are in 30 seconds. You may find it helpful to have a partner to call out 'start counting' and 'stop counting'. You can multiply the number of pulses you have counted by two, to find the pulse rate in beats per minute.

Figure B7.24: Feeling the pulse in the neck.

Method

Work with a partner.

1. Read through the method and construct a table to fill in your results.
2. Ask your partner to sit very still and relax.
   After a few minutes, measure your partner's pulse rate. Do this three times. Record the three values.
3. Ask your partner to do some exercise, such as raising their arms over their head vigorously for one minute or running on the spot. When they stop, measure and record their pulse rate again. Do this, every two minutes, until their pulse rate goes back to the resting value.

Questions

1. Use your results to draw a line graph. Put time (minutes) on the *x*-axis, and pulse rate (beats per minute) on the *y*-axis. Mark on the *x*-axis where exercise began and ended. Use a ruler to join the points with straight lines.
2. Use your table or graph to describe, in words, how exercise affected your partner's pulse rate.
3. Explain why the pulse rate increases when you exercise. Think about:
   - what your muscles do when you exercise
   - how the muscles get the energy to do this
   - how the muscles are supplied with their needs.

   (When you have studied respiration, you will also be able to explain why the pulse rate does not go back to normal immediately after stopping exercise.)

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Blood vessels

There are three main kinds of blood vessel: **artery**, **capillary** and **vein** (Figure B7.25).

Arteries carry blood away from the heart. They divide again and again, and eventually form very tiny vessels called capillaries (Figure B7.26).

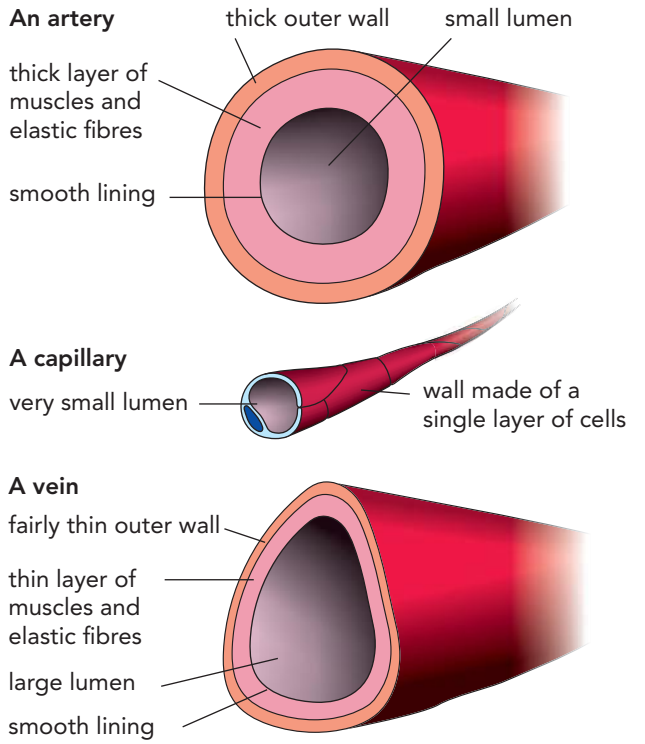

Figure B7.25: Sections through an artery, capillary and vein. The drawings are not to scale. In reality, capillaries are much smaller than either arteries or veins.

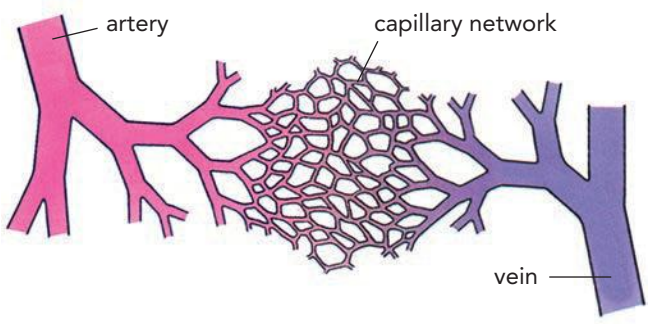

Figure B7.26: Arteries divide to form capillaries, which join up again to form veins.

KEY WORDS

artery: a thick-walled vessel that takes high-pressure blood away from the heart.

capillary: a tiny vessel with walls only one cell thick, that takes blood close to body cells.

vein: a thin-walled vessel that takes low-pressure blood back to the heart.

Veins carry blood towards the heart. They have valves to help to keep the blood flowing in the correct direction.

Capillaries deliver blood containing oxygen and nutrients close to every cell in the body.

The capillaries gradually join up with one another to form large vessels called veins.

Arteries

When blood flows out of the heart, it enters the arteries. This blood is at high pressure, because it has just been forced out of the heart by the contraction of the muscles of the ventricles.

Arteries need very strong walls to withstand the high pressure of the blood flowing through them.

The blood does not flow smoothly through the arteries. It pulses through. The pressure of the blood is high when the muscles in the ventricles contract, and reduces as these muscles relax. The arteries have elastic tissue in their walls which can stretch and recoil (bounce back) with the force of the blood. This helps to make the flow of blood smoother. You can feel your arteries stretch and recoil when you feel your pulse in your neck or wrist.

Capillaries

The arteries gradually divide to form smaller and smaller vessels. These are the capillaries. The capillaries are very small and penetrate to every part of the body. No cell is very far away from a capillary.

The function of the capillaries is to take nutrients, oxygen and other materials to all the cells in the body, and to take away their waste materials. To do this, their walls must be very thin so that substances can get in and out of the capillaries easily. The walls of the smallest capillaries are only one cell thick (Figure B7.27).

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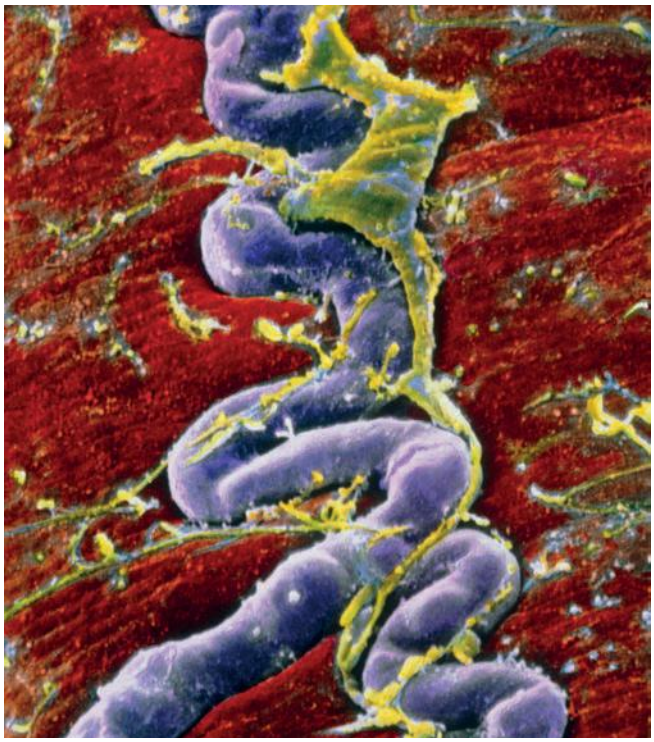

Figure B7.27: A capillary, shown in blue, makes its way through muscle tissue (×600).

Veins

The capillaries gradually join up again to form veins. By the time the blood gets to the veins, it is at a much lower pressure than it was in the arteries. The blood flows more slowly and smoothly than it did in the arteries.

There is no need for veins to have such thick, strong, elastic walls.

If the veins were narrow, this would slow down the blood even more. To help keep the blood moving easily through them, the space inside the veins – the lumen – is much wider than the lumen of the arteries.

Veins have valves in them to stop the blood flowing backwards (Figure B7.28). Valves are not needed in the arteries, because the pressure produced by the heart keeps blood moving forwards through them.

Blood is also kept moving in the veins by the contraction of muscles around them (Figure B7.28). The large veins in your legs are squeezed by your leg muscles when you walk. This helps to push the blood back up to your heart.

Table B7.01 summarises the structure and function of arteries, capillaries and veins.

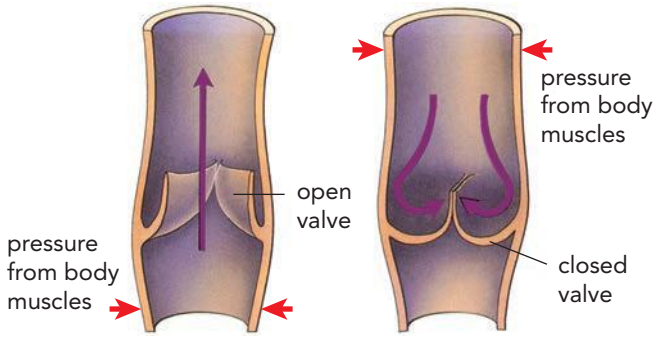

Figure B7.28: Valves in a vein. The valves are like pockets set into the wall of the vein.

Blood vessel	Function	Structure of wall	Width of lumen	How structure fits function
arteries	carry blood away from the heart	thick and strong, containing muscle and elastic tissue	relatively narrow; it varies with heartbeat, because the walls can stretch and recoil	strength and elasticity needed to withstand the high pressure and pulsing of the blood as it is pumped through the arteries by the heart
capillaries	supply all cells with their requirements, and take away waste products	very thin, only one cell thick	very narrow, just wide enough for a red blood cell to pass through	no need for strong walls, as most of the blood pressure has been lost; thin walls and narrow lumen bring blood into close contact with body tissues
veins	return blood to the heart	quite thin, containing far less muscle and elastic tissue than arteries	wide; contains valves	no need for strong walls, as most of the blood pressure has been lost; wide lumen offers less resistance to blood flow; valves prevent backflow

Table B7.01: Structure and functions of arteries, capillaries and veins.

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ACTIVITY B7.03

Comparing plant and animal transport systems

Work in a group of two, three or four for this activity.

Earlier in this chapter, you learnt about how xylem and phloem are involved in transporting substances in plants. Now, you also know how blood vessels transport substances in animals.

In your group, think of at least *two* similarities between the transport system of a plant and the transport system of a human.

Now think of at least *two* differences between them.

Work with the other groups in your class to combine all of your ideas to produce a comparison between the transport systems in a plant and in a human. Perhaps this can go on display in your classroom.

Reflection

Think about how you worked to construct your comparison.

How well do you think you contributed to your group's work? Did other people in the group help you in any way? Did you help others?

Do you think that working in a group like this helps you to understand or remember information better than working on your own?

Questions

B7.23 Name the type of blood vessel that:

- **a** has the thickest wall
- **b** has the thinnest wall
- **c** contains valves.

B7.24 Look at Figure B7.18.

- **a** Where does deoxygenated blood become oxygenated?
- **b** Where does oxygenated blood become deoxygenated?
- **c** Most arteries carry oxygenated blood. Name *one* artery that carries deoxygenated blood.

B7.25 Explain why the walls of arteries need to contain more elastic tissue than the walls of veins.

Blood

Blood is a liquid that contains cells. The liquid part of blood is called **plasma**. Most of the cells that are carried in this liquid are **red blood cells**. A much smaller number are **white blood cells**. There are also small cell fragments called **platelets**; they are formed from special cells in the bone marrow (Figures B7.29 and B7.30).

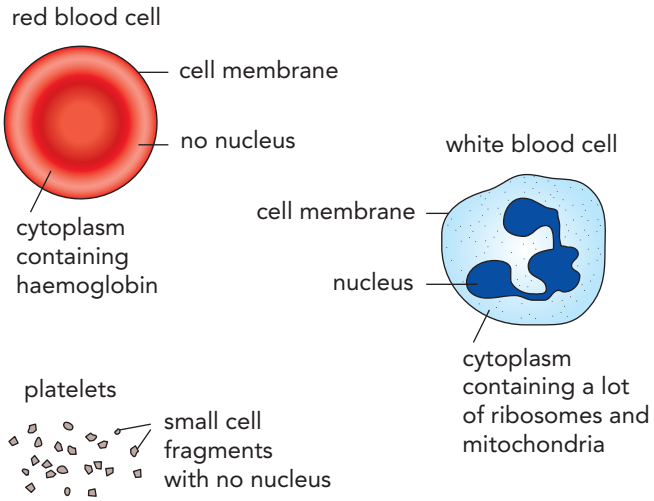

Figure B7.29: The components of blood. These cells and cell fragments float in a pale yellow liquid called plasma.

KEY WORDS

plasma: the liquid part of blood.

red blood cells: biconcave blood cells with no nucleus, which transport oxygen.

white blood cells: blood cells with a nucleus, which help to defend against pathogens.

platelets: tiny cell fragments present in blood, which help with clotting.

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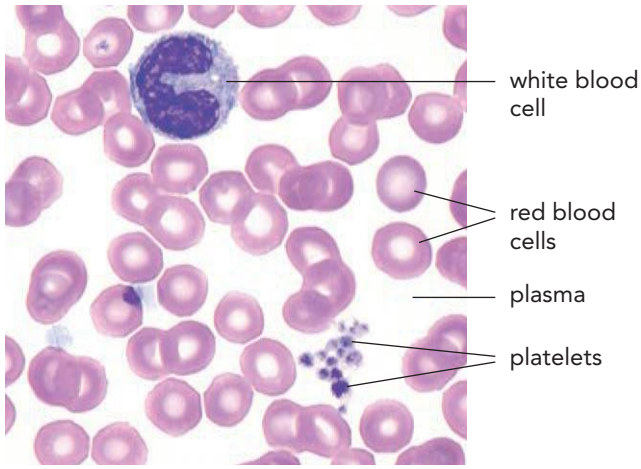

Figure B7.30: A photomicrograph of blood. The blood has been coloured with a stain to make the different kinds of cell show up clearly (×1500).

Red blood cells

Red blood cells are red because they contain the pigment (coloured substance) **haemoglobin**. This carries oxygen. Haemoglobin is a protein, and contains iron. It is this iron that readily combines with oxygen where the oxygen concentration is high. This happens where blood capillaries take the blood close to the alveoli in the lungs. Haemoglobin that is combined with oxygen is called oxyhaemoglobin.

Oxyhaemoglobin readily releases its oxygen where the oxygen supply is low. This happens when the blood passes through capillaries close to cells that are respiring, using up oxygen.

Red blood cells are unusual because they do not possess a nucleus or mitochondria. The lack of a nucleus in a red blood cell means that there is more space for packing in millions of molecules of haemoglobin.

Another unusual feature of red blood cells is their shape. They are biconcave discs – like a flat disc that has been pinched in on both sides. This, together with their small size, gives them a relatively large surface area compared with their volume. This high surface area to volume ratio speeds up the rate at which oxygen can diffuse in and out of the red blood cell.

The small size of the red blood cell is also useful in enabling it to squeeze through even the tiniest capillaries. This means that oxygen can be taken very close to every cell in the body.

White blood cells

White blood cells are easily recognised, because – unlike red blood cells – they have a nucleus. The nucleus is often quite large.

Many white blood cells can move around. They can squeeze out through the walls of blood capillaries into all parts of the body. Their function is to fight pathogens (disease-causing microorganisms), and to clear up any dead body cells.

Some white blood cells destroy pathogens by engulfing them (taking them into their cytoplasm) and digesting them. This is called **phagocytosis** (Figure B7.31).

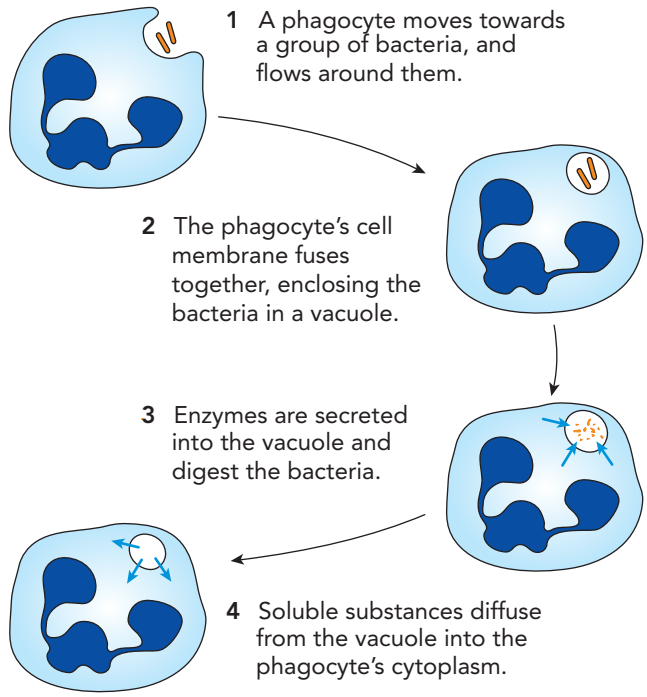

Figure B7.31: How a white blood cell destroys bacteria by phagocytosis.

Other white blood cells produce molecules called antibodies. These molecules attach to pathogens and help to destroy them.

White blood cells that destroy pathogens by phagocytosis are called **phagocytes**. Most phagocytes have a lobed nucleus, like the ones in Figures B7.29 and B7.30.

KEY WORDS

haemoglobin: a red pigment found in red blood cells, which can combine reversibly with oxygen; it is a protein.

phagocytosis: taking bacteria or other small structures into a cell's cytoplasm, and digesting them with enzymes.

phagocytes: white blood cells that destroy pathogens by phagocytosis.

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White blood cells that produce antibodies are called **lymphocytes**. They usually have a large, round nucleus that almost fills the cell (Figure B7.32).

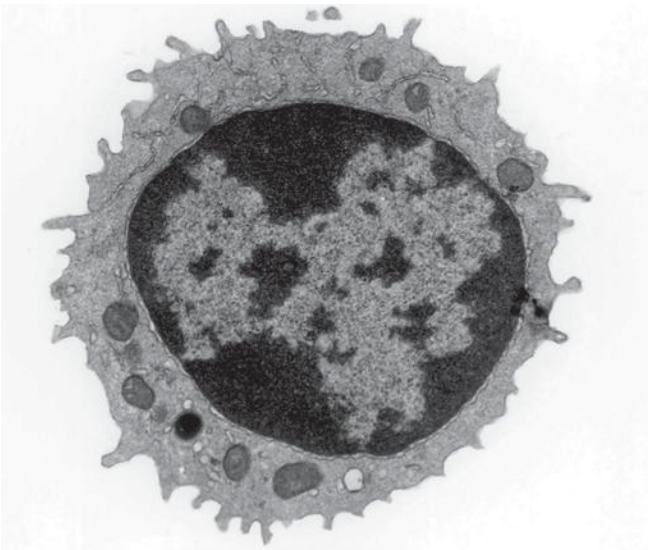

Figure B7.32: Electron micrograph of a lymphocyte ×5000.

KEY WORD

lymphocytes: white blood cells that secrete antibodies.

Platelets

Platelets are small fragments of cells, with no nucleus. They are made in the red bone marrow, and they are involved in blood clotting.

Blood clotting stops pathogens getting into the body through breaks in the skin. Normally, your skin provides a very effective barrier against the entry of bacteria and viruses. Blood clotting also prevents too much blood loss.

The platelets stick together to form clumps. The fibres, the trapped red blood cells and the clumps of platelets form a blood clot.

Plasma

Blood plasma is mostly water. Many substances are dissolved in it. Soluble nutrients such as glucose, amino acids and mineral ions are carried in the plasma.

Plasma also transports hormones such as adrenaline and waste products, including carbon dioxide and urea.

Questions

B7.26 State how you can distinguish a white blood cell from a red blood cell in a photomicrograph.

B7.27 Explain how you can tell the difference between a phagocyte and a lymphocyte, in a photomicrograph.

B7.28 Write one or two sentences that explain, in your own words, what blood plasma is.

ACTIVITY B7.04

Summarising the functions of blood components

Work in a group of three or four for this activity.

You will need a large sheet of paper, to make an illustrated table that can be displayed.

In your group, discuss what your table will look like. You might like to have three columns: one for the component of blood, one for a description or picture of the structure of this component, and a third for a description of its functions.

Try to make your table:

- really easy to understand
- colourful and eye-catching
- full of relevant and clearly explained information.

Peer assessment

When all the groups have completed their tables, they can all be displayed on the wall.

Take some time to look carefully at the tables that other groups have produced. Make a note of at least one good point about each table, and at least one thing that could be improved.

Share your ideas with the other groups, and listen to their ideas about your table.

Is there anything that another group has done that you wish you had thought of?

What do other groups like about your table?

What do other groups suggest you could have done better?

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PROJECT B7.01 DECREASING THE RISK OF CORONARY HEART DISEASE

Work in a group of three or four for this activity.

You are going to produce a leaflet that can help people to reduce their risk of developing coronary heart disease.
Here are some things to think about as you design the leaflet.

- Who will read your leaflet?
- How will the leaflet be distributed to people?
- Keep it simple. People get confused if they are given too much information at once.
- Make it look attractive. A carefully thought-out picture or diagram can be much more interesting and easier to understand than a lot of words.
- Keep it positive. Do not make people feel hopeless about their present lifestyle. Try to help them to feel that they can easily make small changes that will make a difference.
- Be informative. People are much more likely to take action if they understand the reasons why it is important to do so.

You can produce your leaflet by hand, or you can construct it using a computer or tablet.

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SUMMARY

In plants, xylem transports water and mineral ions and supports the plant. Phloem transports sucrose and amino acids.
In roots, xylem and phloem are found in the centre, but in stems they are arranged in groups close to the outer edge. In leaves, they are found in the veins.
The large surface area of root hair cells helps them to absorb water and mineral ions.
Water moves from root hair cells through the root cortex, through the xylem and into the mesophyll cells in leaves.
Transpiration is the movement of water vapour from the air spaces in a leaf into the air outside the leaf, through stomata.
The water vapour in the air spaces comes from the mesophyll cells, as it evaporates from their cell walls.
High temperature increases the rate of transpiration.
High temperature increases kinetic energy of molecules, which speeds up evaporation and diffusion. Low humidity increases the diffusion gradient for water vapour from the air spaces into the surrounding air.
Translocation is the transport of sucrose and amino acids from sources to sinks, in phloem tubes.
The mammalian circulatory system has blood vessels, a pump and valves.
Mammals have a double circulation, where blood passes through the heart twice on one complete circuit. Fish have a single circulation system.
The heart has a muscular wall, a septum, left and right ventricles and atria, one-way valves and coronary arteries.
Blood is pumped away from the heart in arteries and returns to the heart in veins.
Pulse rate and the sounds of valves closing can be used to monitor the activity of the heart.
Coronary heart disease is caused when the coronary arteries become blocked. Risk factors for CHD include diet, sedentary lifestyle, stress, smoking, genes, age and gender.
Arteries have a thicker wall than veins and a smaller lumen. Veins have valves. Capillaries have very thin walls.
The differences between the structures of arteries and veins are related to the higher and more fluctuating pressure of blood in arteries than in veins.
Blood is made up of plasma, red blood cells, white blood cells and platelets.
Red blood cells transport oxygen. White blood cells protect against pathogens. Platelets help with blood clotting. Plasma transports blood cells, ions, nutrients, urea, hormones and carbon dioxide.

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PRACTICE QUESTIONS

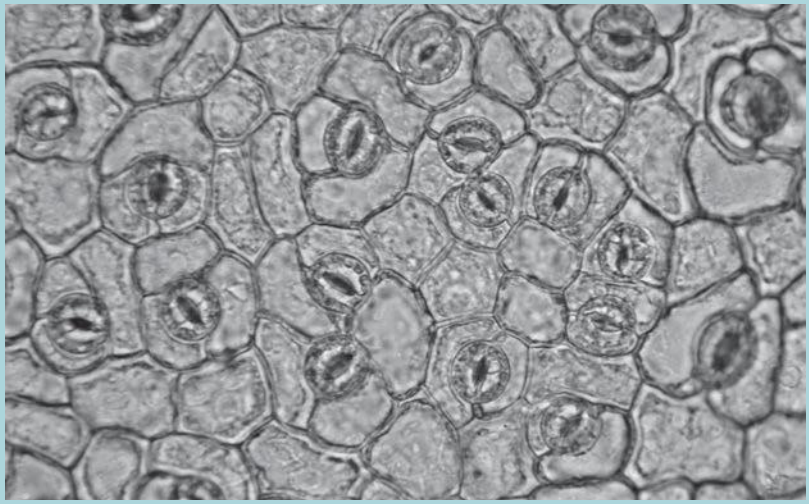
1 **Identify** the word which best completes this sentence.

Water evaporates from the _____ cells in the leaves and then diffuses out of the stomata.

A epidermal
B guard
C mesophyll
D xylem **[1]**

2 **a** Leaves lose water vapour through their stomata.

The micrograph shows a surface view of the lower epidermis of a leaf.



The area of the leaf shown in the micrograph is 0.06 mm^2.

Calculate the mean number of stomata per mm^2 of the surface of the lower epidermis.

Give your answer to the nearest whole number. **[2]**

b **Explain** the importance of each of the following in the movement of water through a plant.

i There are many interconnecting air spaces between the mesophyll cells in a leaf. **[3]**

ii Root hairs have a large surface area. **[2]**

c **Describe** *two* ways in which transport in phloem differs from transport in xylem. **[2]**

[Total: 9]

COMMAND WORD

identify: name/select/recognise.

COMMAND WORDS

calculate: work out from given facts, figures or information.

explain: set out purposes or reasons/make the relationships between things evident/provide why and/or how and support with relevant evidence.

describe: state the points of a topic/give characteristics and main features.

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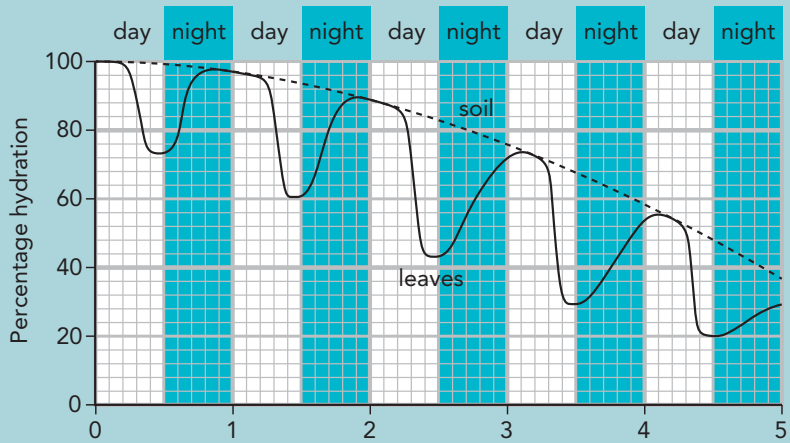
CONTINUED

3 Stomata open to allow carbon dioxide to diffuse into leaves. However, if the plant is short of water, stomata may close to prevent loss of water vapour.

a Explain why it is important to a plant to allow carbon dioxide to diffuse into its leaves. **[2]**

b Water vapour diffuses out of a plant's leaves. Explain where this water vapour comes from. **[2]**

c The cells in the leaves of a plant growing in hot conditions can become partly dehydrated. This means that they contain less water than normal. The graph shows how the percentage hydration of a plant's leaves, and the hydration of the soil, changed during a period of five days without any rainfall.



i Use the data in the graph to describe how the hydration of the leaves changes during the five days without rainfall. **[5]**

ii **Suggest** an explanation for the trend and pattern you have described in your answer to **i**. **[4]**

iii **Predict** the appearance of the plant on day 5. Explain your prediction. **[3]**

[Total: 16]

4 **Give** the component of blood that transports dissolved carbon dioxide. **[1]**

COMMAND WORDS

suggest: apply knowledge and understanding to situations where there is a range of valid responses in order to make proposals/put forward considerations.

predict: suggest what may happen based on available information.

give: produce an answer from a given source or recall/memory.

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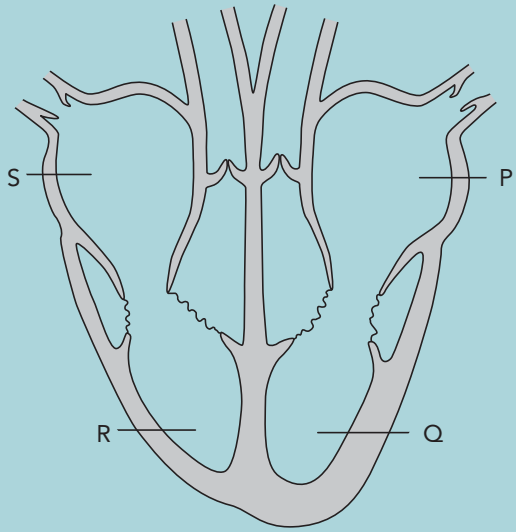
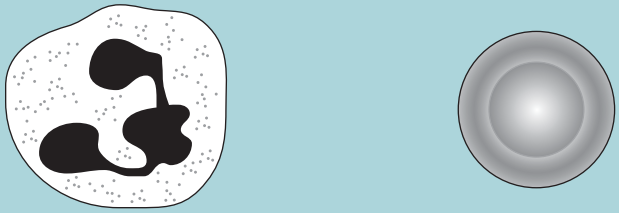
CONTINUED

5 The diagram shows a section through the heart.



Identify the *two* areas that contain deoxygenated blood. **[2]**

6 The figure shows a white blood cell and a red blood cell.



a **State** *two* features of the white blood cell that differ from the red blood cell. **[2]**

b The diameter of a red blood cell is 0.007 mm.

Measure the diameter of the red blood cell in the figure.

Use your measurement to calculate the magnification of the diagram.

Show your working. **[3]**

c Red blood cells transport oxygen.

Explain how red blood cells take up oxygen, and how they transport it to respiring cells. **[3]**

d State the function of white blood cells. **[1]**

[Total: 8]

COMMAND WORD

state: express in clear terms.

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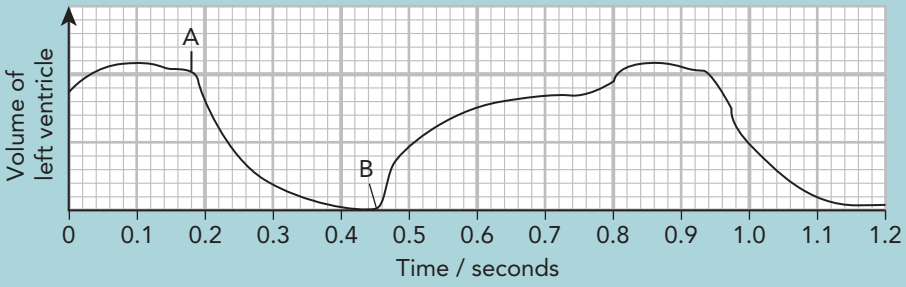
CONTINUED

7 **a** **Outline** *two* ways in which the activity of the heart can be monitored. **[2]**

b Describe how the activity of the heart changes when a person exercises and then rests. **[3]**

[Total: 5]

8 The graph below shows how the volume of the left ventricle changes over a time period of 1.2 seconds.



a Describe what the muscle in the wall of the left ventricle is doing at points A and B on the graph. **[2]**

b Use the graph to **determine** the time for one complete heartbeat. **[1]**

c Use your answer to **b** to calculate the heart rate in beats per minute. **[2]**

d Make a copy of the graph. On your copy, **sketch** a line to show the volume of the right ventricle during this 1.2 second period. **[2]**

[Total: 7]

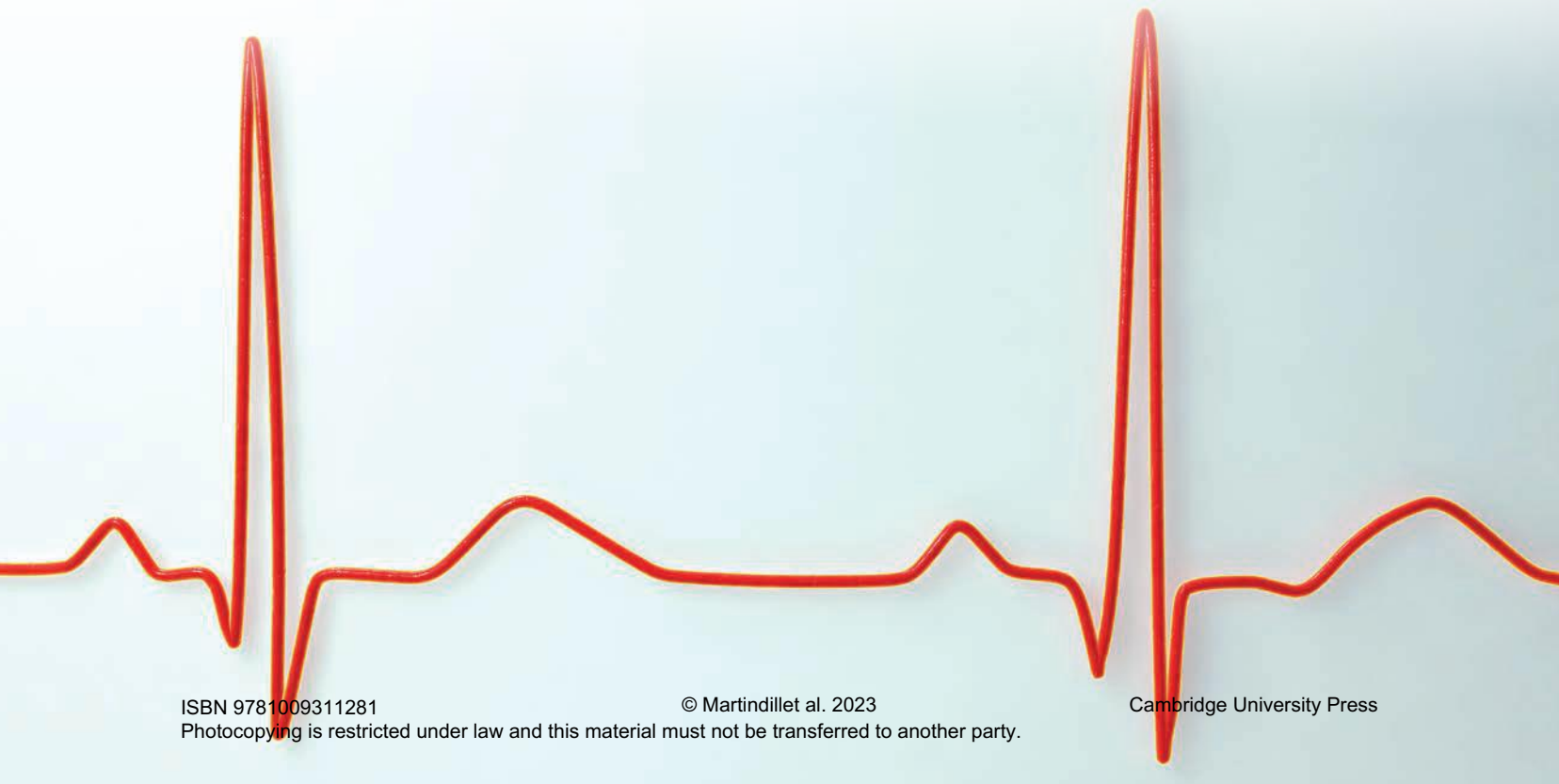
COMMAND WORD

outline: set out main points.

COMMAND WORDS

determine: establish an answer using the information available.

sketch: make a simple freehand drawing showing the key features, taking care over proportions.



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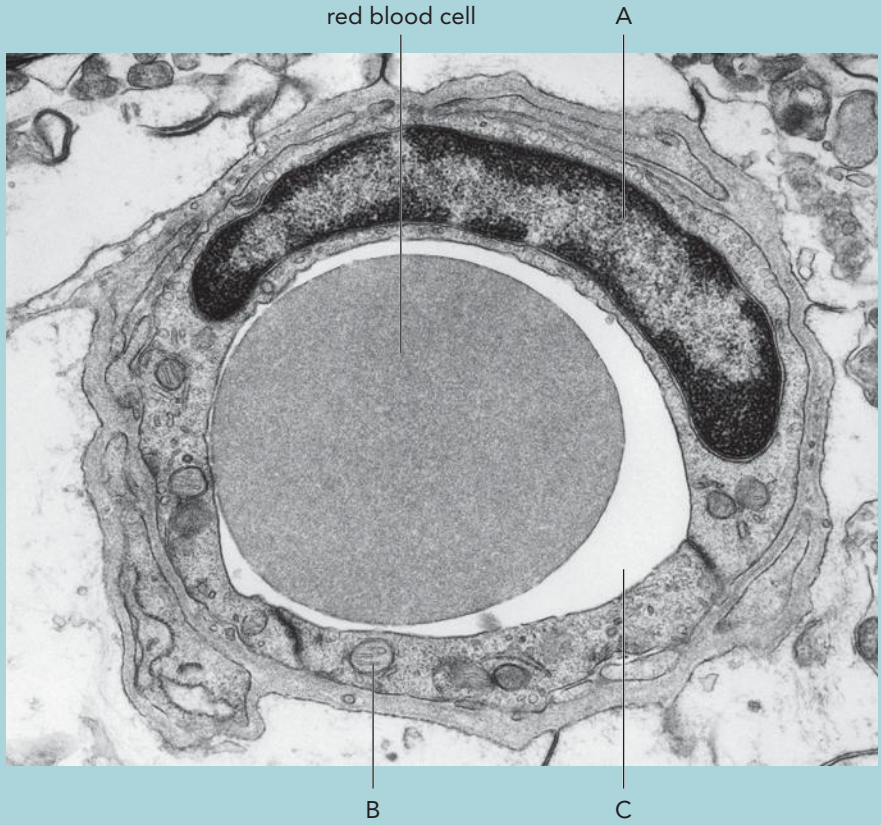
CONTINUED

9 The diagram shows a red blood cell inside a capillary.



a Structures A and B are inside a cell that forms the wall of the capillary.

i Identify structures A and B. **[2]**

ii Explain why it is important that the wall of the capillary is only one cell thick. **[2]**

iii Explain the advantages of the capillary being only just wide enough for the red blood cell to pass through it. **[2]**

b Describe *three* ways in which the structure of the red blood cell differs from the cells in the wall of the capillary. **[3]**

c Identify the liquid labelled C. **[1]**

[Total: 10]

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SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
state the functions of xylem and phloem	B7.01			
identify the positions of xylem and phloem in roots, stems and leaves	B7.01			
identify root hair cells and state their functions	B7.01			
explain how the structure of a root hair is related to its function	B7.01			
describe the pathway taken by water from soil to leaves	B7.01			
investigate the pathway of water through the above-ground parts of a plant	B7.01			
explain what transpiration is, and how it happens	B7.01			
investigate and describe the effects of variation of temperature and wind speed on transpiration rate	B7.01			
explain the importance of the large surface area of the mesophyll cells	B7.01			
explain how temperature and humidity affect transpiration rate	B7.01			
explain how and why wilting occurs	B7.01			
explain what is meant by translocation	B7.01			
describe the structure of the circulatory system	B7.02			
describe the structure of the heart	B7.02			
explain the relative thickness of the walls of the atria and ventricles, and the left and right ventricles	B7.02			
describe the functioning of the heart in terms of the contraction of muscles and the action of valves	B7.02			
state that the activity of the heart can be monitored by measuring pulse rate and listening to the valves closing	B7.02			
investigate and describe how exercise affects heart rate	B7.02			
explain how exercise affects heart rate	B7.02			
describe coronary heart disease (CHD) and list factors that increase the risk of developing CHD	B7.02			

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CONTINUED

I can	See topic . . .	Needs more work	Almost there	Confident to move on
describe the structures of arteries, veins and capillaries	B7.02			
explain how the structures of arteries and veins are related to their functions	B7.02			
explain how the structure of a capillary is related to its functions	B7.02			
identify red blood cells, white blood cells and platelets in micrographs and diagrams	B7.02			
describe the functions of plasma, red blood cells, white blood cells and platelets	B7.02			
state the function of blood clotting.	B7.02			

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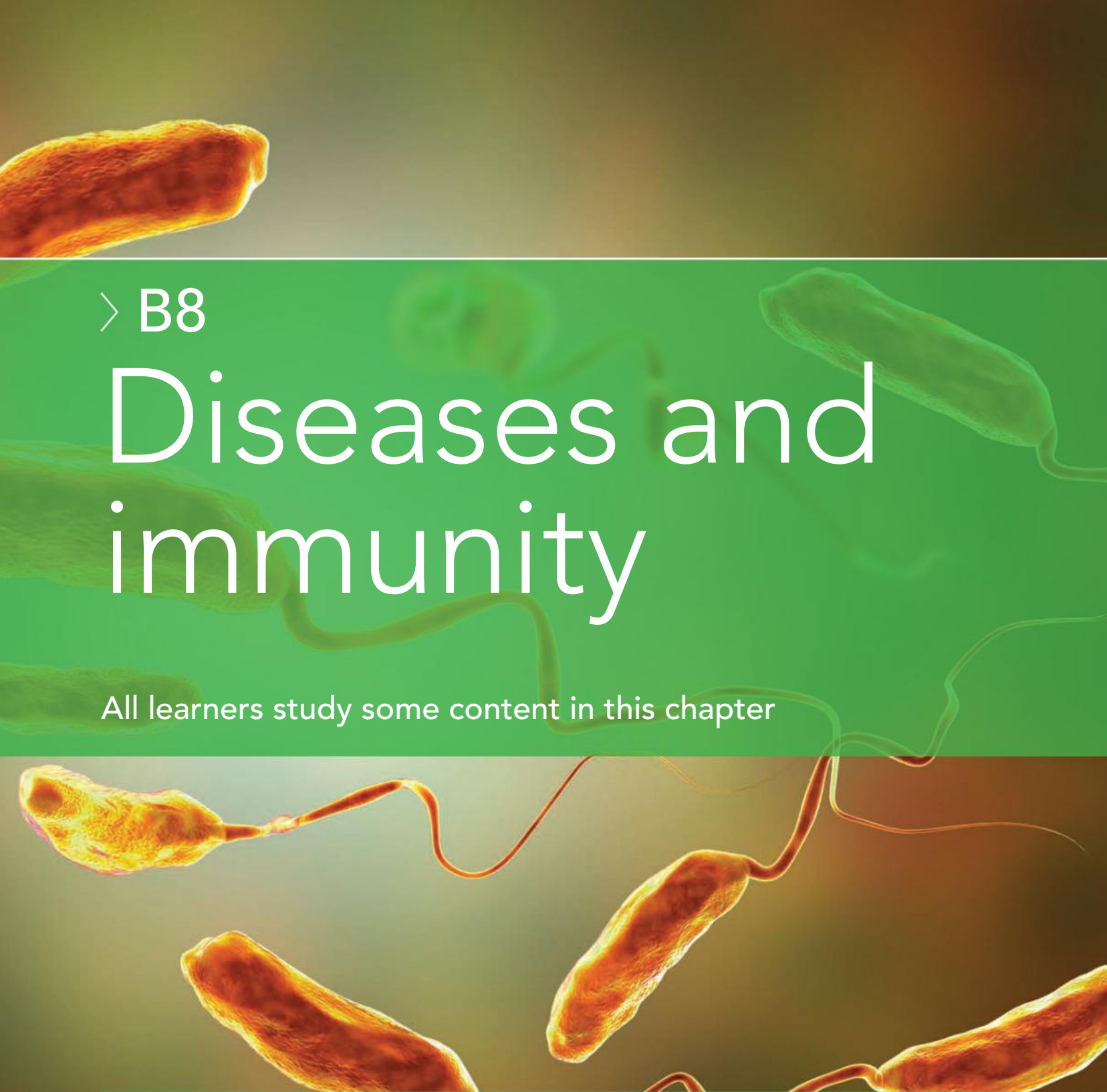

B8 Diseases and immunity

All learners study some content in this chapter

IN THIS CHAPTER YOU WILL:

- learn about what pathogens are, and how they are transmitted from one host to another
- learn how the body defends itself against pathogens
- learn about some important ways to control the spread of disease
- explain what immunity is, and how it is produced naturally and through vaccination.

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BEFORE YOU START

Here is a list of words that you have already used in your biology course.

antibody bacterium pathogen virus white blood cell

- Try to write a sentence that includes all of those words. You can use plurals instead of singular words, if you like. If you cannot fit all the words into one sentence, try writing two sentences.
- Take turns with others to read out your sentence or sentences.
- Who has written the best sentence? What makes this the best sentence?

SCIENCE IN CONTEXT B8.01

Global outbreaks of measles

Measles used to be a very common disease, particularly in young children. Although many people who get measles recover fully, it can lead to serious complications, and even death.

In most countries, children are vaccinated against measles. The vaccine gives almost complete protection, and cases of measles fell dramatically when the vaccine first began to be used in the late 1960s and 1970s. However, in 2019 there was a significant increase in numbers of measles cases, with serious outbreaks happening in Ukraine, the Democratic Republic of the Congo (DRC), Madagascar, Angola, Cameroon, Chad, Kazakhstan, Nigeria, Philippines, South Sudan, Sudan, and Thailand. Numbers of cases also increased in developed countries such as the USA, which had its highest number of cases for 25 years. Worldwide, three times more cases of measles were reported in 2019 than in 2018.

What happened? The virus that causes measles is very easily spread from one person to another. If at least 95% of people in a community are vaccinated against measles, then even the ones who are not vaccinated are unlikely to get the disease. This is because there are not enough 'hosts' for the measles virus to live in. This helps to protect vulnerable children and adults, such as those who have a weak immune system. But not every country manages to vaccinate this percentage of children. And, increasingly, some parents are choosing not to have their children vaccinated.

Figure B8.01: This child has just been vaccinated against a number of common childhood diseases, including measles.

Discussion questions

1 Why might some parents choose not to have their children vaccinated against measles?

2 Some schools refuse to allow children who have not been vaccinated to come to classes. Do you think this is a good idea?

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B8.01 Pathogens and transmissible diseases

A pathogen is a microorganism (a tiny organism that can only be seen with a microscope) that causes disease. Many diseases are caused by pathogens that get into our bodies and breed there, such as the virus shown in Figure B8.02.

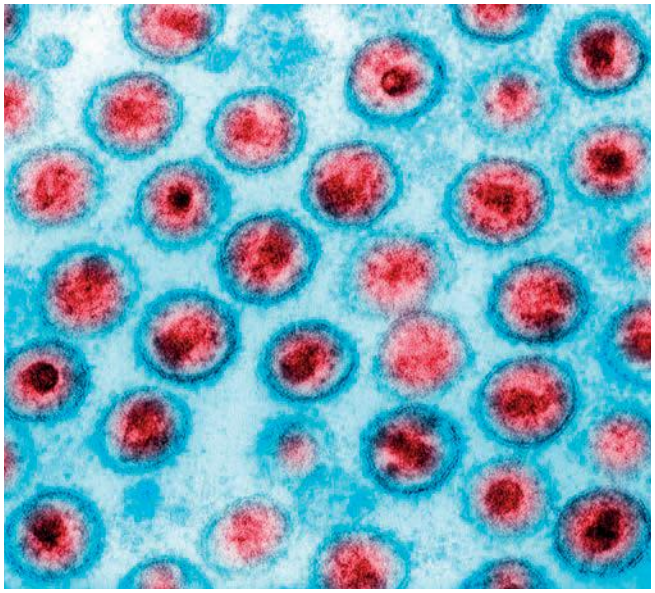

Figure B8.02: An electron micrograph of human immunodeficiency viruses (HIV). The colours are not real. They have been added to make the viruses show up more clearly. The blue circles are the protein coats, and the genetic material is contained in the red areas. Each virus is about 0.1 µm across.

All viruses are composed of a protein coat surrounding genetic material.

Table B8.01 shows the four kinds of microorganism that can act as pathogens, and some of the diseases that they cause.

Group to which pathogen belongs	Examples of diseases which they cause
viruses	influenza, common cold, poliomyelitis, measles, AIDS
bacteria	cholera, syphilis, whooping cough, tuberculosis, tetanus
protoctists	malaria, amoebic dysentery
fungi	athlete's foot, ringworm

Table B8.01: Types of pathogen.

A person or other animal in which the pathogen lives and breeds is called a **host**. Diseases that are caused by pathogens can usually be passed from one host to another. They are called **transmissible diseases**.

Once inside the body, some pathogens damage our cells by living in them and using up their resources. Others cause harm to cells and body systems by producing waste products, called **toxins**, which spread around the body and cause **symptoms** such as high temperature and rashes and make you feel ill. Some toxins produced by pathogens are among the most dangerous poisons in the world. An example is the toxin produced by the bacterium *Clostridium botulinum*.

KEY WORDS

host: an organism in which a pathogen lives and reproduces.

transmissible disease: a disease that can be passed from one host to another; transmissible diseases are caused by pathogens.

toxin: a poisonous substance; a chemical that damages cells.

symptoms: features that you experience when you have a disease.

Transmission of pathogens

The movement of a pathogen from one host to another is called **transmission**. The entry of the pathogen into the body is known as **infection**. There are several ways in which transmission and infection can happen.

Direct contact

Some pathogens pass from one person to another when there is direct contact between an infected person and an uninfected one. Diseases transmitted in this way are known as transmissible diseases (sometimes called contagious diseases). For example, the virus that causes AIDS, called HIV (the human immunodeficiency virus) can be transmitted when an infected person's blood comes into contact with another person's blood. The fungus that causes athlete's foot, a skin infection, can be passed on by sharing a towel with an infected person.

KEY WORDS

transmission: the movement of a pathogen from one host to another.

infection: the entry of a pathogen into the body of a host.

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Indirect transmission

Most pathogens are transmitted indirectly. This can happen through:

- breathing in droplets containing pathogens
- touching a surface that someone with the pathogen has touched
- eating food or drinking water that contains pathogens
- contact with animals that are carrying pathogens.

Cold, influenza and COVID-19 viruses are carried in the air in tiny droplets of moisture. Every time someone with these illnesses speaks, coughs or sneezes, millions of viruses are propelled into the air (Figure B8.03). If you breathe in the droplets, you may become infected. You can also pick up these viruses if you touch a surface on which they are present, and then put your hands to your face.

Figure B8.03: A sneeze propels tiny droplets of moisture, containing millions of viruses, into the air. Catch your sneeze in a tissue!

Bacteria such as *Salmonella* can enter your alimentary canal with the food that you eat. If you eat a large number of these bacteria, you may get food poisoning. Fresh foods, such as fruit and vegetables, should be washed in clean water before you eat them. Cooking usually destroys bacteria, so eating recently cooked food is generally safe. Food bought from street stalls is safe if it is hot and has just been cooked. However, you need to take care with anything that has been kept warm for a while, as this gives any bacteria on it a chance to breed (Figure B8.04). Many governments make sure that food sellers are checked regularly to make sure that they are using good hygiene, and that their food is safe to eat.

Figure B8.04: This food from a street stall is safe to eat because it has just been cooked, and the seller has reduced the risk of contaminating it with harmful bacteria by wearing gloves to protect the food.

Many pathogens, including the virus that causes poliomyelitis and the bacterium that causes cholera, are transmitted in water. If you swim in water that contains these pathogens, or drink water containing them, you run the risk of catching these diseases (Figure B8.05). These pathogens can also get onto your hands if you touch anything that contains them. They can then be passed into your body when you eat food that you have touched, or touch your mouth with your fingers.

Figure B8.05: Contaminated water such as this almost certainly contains pathogens that would cause disease if they got into a person's body.

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ACTIVITY B8.01

Transmissible diseases

To start with, work on your own.

Think about any transmissible diseases that you, or someone you know, may have had. Make a list.

What kind of pathogen do you think caused each disease?

How do you think that pathogen got into the body?

Now share your ideas with your partner. Are there any transmissible diseases that you have both listed? Do you agree about the kinds of pathogen that caused these diseases? Do you agree about how the pathogen got into the body? If you do not agree, use the internet to check who is right.

Reflection

When you are searching for reliable information on the internet, what tactics do you use? How do you decide on your search terms?

How do you decide whether you can trust the information on a particular website?

Body defences

The human body has many natural defences against pathogens. Some of them prevent pathogens from getting to parts of the body where they could breed. Figure B8.06 shows some of these defences.

Pathogens that manage to get through all of these defences are usually destroyed by white blood cells. In Chapter B7, we saw that some of these cells take in and digest the pathogens by phagocytosis, while others produce chemicals called antibodies that incapacitate or directly kill the pathogens.

Questions

B8.01 Explain what is meant by a transmissible disease.

B8.02 The pathogens that cause some transmissible diseases are passed on by direct contact. How does the skin help to protect us against the entry of these pathogens?

B8.03 How does stomach acid protect us against transmissible diseases?

Controlling the spread of disease

A clean water supply

We use water for many different purposes each day, especially for drinking, washing and in preparing food. Water that has not been made safe to drink – for example, from a dirty container or from a river or lake – can contain many different pathogens. Some of these are very dangerous, such as the bacterium that causes cholera (see Topic B8.02) or the virus that causes polio.

A clean water supply is one of the most basic health needs. In many countries, clean, safe water is supplied to homes and industries by a network of pipes. Before entering the pipes, the water is filtered to remove dirt, and then treated with chlorine to kill all the microorganisms in it. Where there is no piped water supply, people may be able to collect clean water from a communal source, such as a tap or deep well (Figure B8.07).

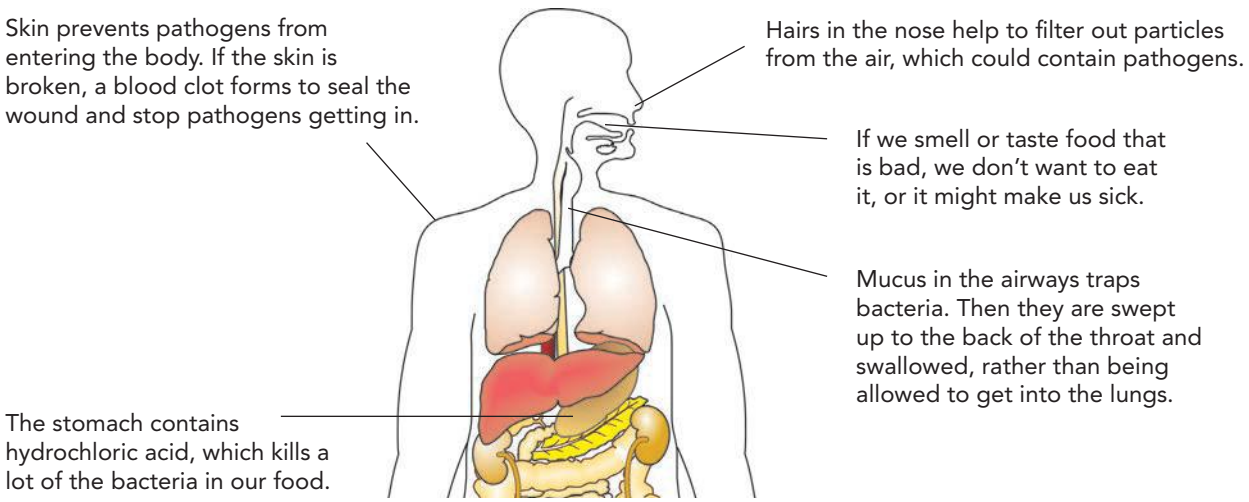

Figure B8.06: Body defences against the entry of pathogens.

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Figure B8.07: Where clean water is not supplied through pipes, a deep well can be the best source of water. It is even better if the water is boiled before use, to kill any pathogens it might contain.

Hygienic food preparation

Good food hygiene makes it much less likely that someone eating the food you have prepared will get ill. Most food poisoning is caused by bacteria, so understanding the conditions that bacteria need for growth and reproduction can help us to keep them under control. A few simple rules can prevent you, or anyone else eating food you have prepared, from getting food poisoning.

1 Keep your own bacteria and viruses away from food. Always wash your hands before touching or eating food or putting your hands into your mouth for any reason. Keep your hair out of food. People working in food preparation environments often wear uniforms that cover their clothes and hair (Figure B8.08). Never cough or sneeze over food.

2 Keep animals away from food. Animals are even more likely to have harmful bacteria on them than you are, so they should never be allowed to come into contact with food.

   Some are particularly dangerous. Houseflies usually have harmful bacteria on their feet because they may have been walking on rubbish, faeces or dead animals. And when flies feed, they spit saliva onto the food (Figure B8.09). Rats and mice often carry pathogens. Covering food to keep flies and other animals from touching it is always a good idea.

Figure B8.08: Preparing food in a hospital kitchen.

Figure B8.09: Houseflies can transmit pathogens to food, on their feet and in their saliva.

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3 Do not keep foods at room temperature for long periods. Figure B8.10 shows how bacterial growth and reproduction are affected by temperature. If there are even just a few harmful bacteria on food, these can reproduce and form large populations if the temperature is right for them. Keeping food in the fridge slows down bacterial growth. Cooking food at a high temperature will kill most bacteria. If cooked food is reheated, it should be made really hot, not just warmed.

4 Keep raw meat away from other foods. Raw meat often contains bacteria. This is not a problem if the meat is to be cooked, because these bacteria will be killed. However, if the bacteria get onto other foods that might be eaten raw, then they might breed there. In any case, foods such as salads and vegetables that are to be eaten raw should be washed in clean water before eating, unless they have been packaged so that they cannot be contaminated with bacteria.

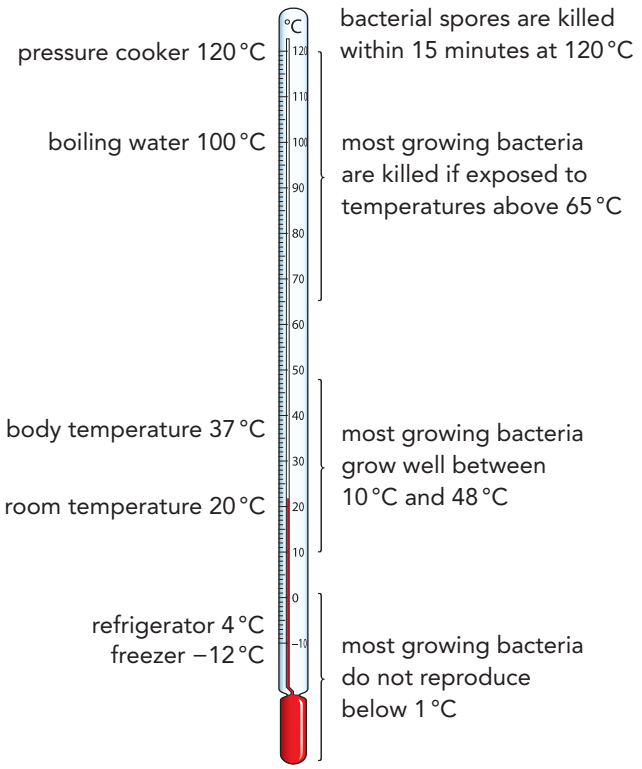

Figure B8.10: The effect of temperature on bacterial growth.

Good personal hygiene

Personal hygiene means keeping your body clean. This can greatly reduce the risk of getting, or passing on, transmissible diseases. We have already seen how important this is when preparing or eating food.

Human skin makes an oil that helps to keep it supple and waterproof. If the skin is not washed regularly, this oil can build up, as can dirt from things that we have touched.

When we are hot, we produce sweat from sweat glands in the skin. The evaporation of water from the sweat helps us to keep our body temperature from rising too high. If oil, dirt and sweat are left on the skin for long, they provide breeding grounds for bacteria. These can produce substances that smell unpleasant. Washing regularly, using soap and shampoo to help to remove oils, prevents this from happening (Figure B8.11).

Figure B8.11: Washing with soap reduces the risk of transferring pathogens.

There are also millions of bacteria inside our mouths. Most of these are harmless and may even be beneficial to us. But some of them can cause bad breath and tooth decay. Brushing teeth twice a day, and perhaps also using a mouthwash, can keep these harmful bacteria under control.

Waste disposal

We produce an enormous amount of rubbish each year. Waste food, cardboard and paper packaging, bottles and cans, newspapers and magazines, plastic bags, old tyres – anything that we have finished with and no longer want to use – are all thrown away.

Sometimes, this waste simply accumulates close to where people live and work (Figure B8.12). Animals such as houseflies, rats and stray dogs may forage for food in the rubbish. Bacteria breed in the waste food. Dangerous chemicals seep out of the rubbish, polluting the ground and waterways.

In many countries, waste is regularly collected and taken to landfill sites. In some places, nothing is done to make the landfill site safe, but good management can avoid risk of infection and pollution. Figure B8.13 shows a well-designed

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landfill site. Only licensed operators are allowed to add material to the site, and the rubbish is checked as it is brought in, to make sure that nothing really dangerous is included. The rubbish is added in even layers and is compacted (pressed down) to reduce the space it takes up.

Some of the rubbish in the landfill site is rotted by decomposers, especially bacteria. This produces a gas called methane, which is flammable and could cause explosions if it is allowed to build up. Placing pipes in the rubbish can allow the methane to escape harmlessly into the air. Better still, the methane can be collected and used as a fuel.

Figure B8.12: Waste – especially food waste – left in the street encourages rats and other animals, which can spread pathogens.

Eventually, when the landfill site is full, it can be covered over with soil and grass, and trees allowed to grow.

Sewage treatment

Sewage is waste liquid that has come from houses, industry and other parts of villages, towns and cities. Some of it has just run off streets into drains when it rains. Some of it has come from toilets, bathrooms and kitchens in people's houses and offices. Some of it has come from factories. Sewage is mostly water, but also contains many other substances. These include urine and faeces, toilet paper, detergents, oil and many other chemicals.

Sewage should not be allowed to run into rivers or the sea before it has been treated (Figure B8.14). This is because it can harm people and the environment. Untreated sewage is called raw sewage.

Figure B8.14: This open drainage canal contains rubbish and raw sewage – a major health risk to people living in this area.

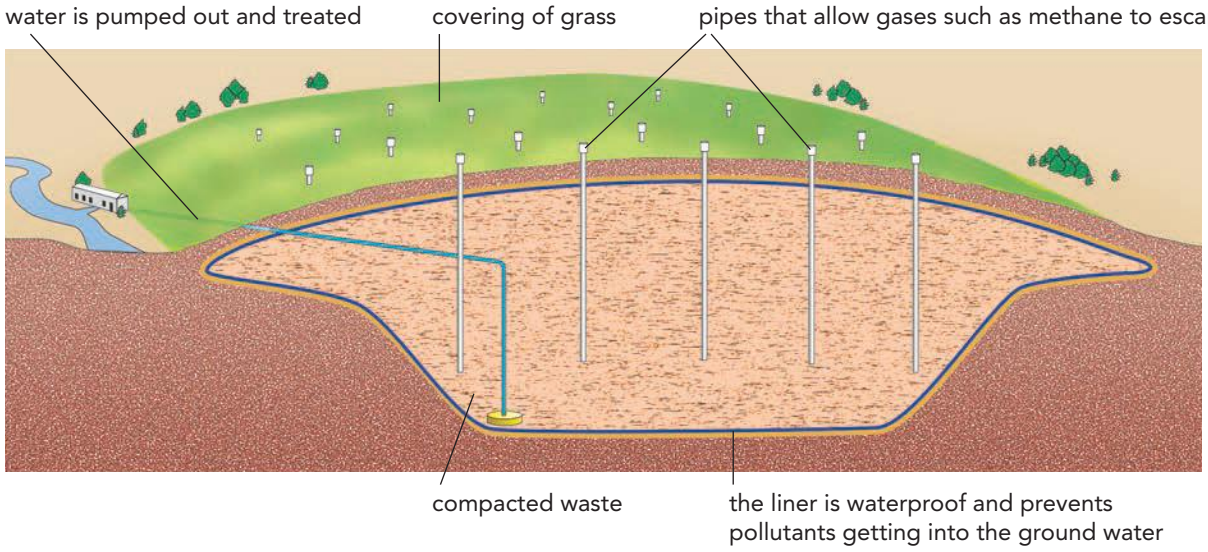

Figure B8.13: A well-constructed landfill site.

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Raw sewage contains many bacteria and other microorganisms, some of which are likely to be pathogens. People who come into contact with raw sewage may get ill, especially if it gets into their mouths. Poliomyelitis and cholera are just two of the serious diseases that can be transmitted through water polluted with raw sewage.

ACTIVITY B8.02

Controlling the spread of disease

Work in a group of three or four for this activity.

Your task is to summarise the importance of a clean water supply, hygienic food preparation, personal hygiene, and safe disposal of sewage and other waste. Your summary should be in a form which can be shared with others.

Decide on the form that your summary could take. It could be a series of slides, a video presentation, a poster or an illustrated summary table.

You can use the information in this book, or you may like to research more information on the internet.

Peer assessment

Share your summary with another group or groups.

Look at their summary and decide on at least *two* things that they have done very well. Then suggest *two* things that would improve their summary.

Then consider the feedback that the other group gives to you. Do you agree with it? If you can, use their suggestions to improve your summary.

Questions

B8.04 Explain why a clean water supply is very important to maintain health.

B8.05 Suggest why a deep well can provide a safer source of water than a river or lake.

B8.06 Explain why food that is not going to be eaten immediately should be:

- **a** kept covered
- **b** kept in a fridge.

B8.02 The immune response

In Chapter B7, we saw that one type of white blood cell – lymphocytes – produces molecules called antibodies. Antibodies help to destroy pathogens.

Antibodies

In your body, you have thousands of different kinds of lymphocyte. Each kind is able to produce a different sort of antibody.

An antibody is a protein molecule with a particular shape. This shape is complementary to the shape of another molecule, which is called an **antigen**.

KEY WORD

antigen: a chemical that is recognised by the body as being 'foreign' (i.e. it is not part of the body's normal set of chemical substances) and stimulates the production of antibodies.

Many antigens are molecules found on the outside of a pathogen. Each pathogen has its own antigens, which have specific shapes. To destroy a particular pathogen, antibody molecules must be made which are a perfect complementary shape to the antigens on the pathogen.

The antibody molecules bind with the antigen (Figure B8.15). In some cases, this directly kills the pathogen. In other cases, the antigens stick the pathogens together. This stops the pathogens dividing or moving, making it easier for phagocytes to destroy them.

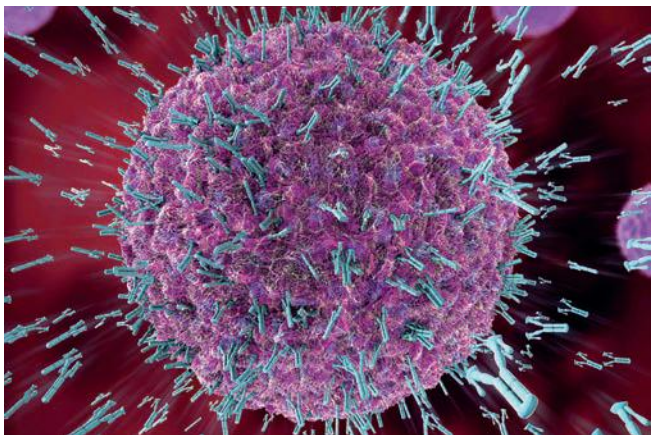

Figure B8.15: This computer-generated image shows antibodies binding to their antigens on a virus. The antibody molecules are the Y-shaped blue structures.

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Most of the time, most of your lymphocytes do not produce antibodies. It would be a waste of energy and materials if they did. Instead, each lymphocyte waits for a signal that a pathogen which can be destroyed by its particular antibody is in your body.

If a pathogen enters the body, it is likely to meet a large number of lymphocytes. One of these may recognise the pathogen as being something that its antibody can destroy. This lymphocyte will start to divide rapidly by mitosis, making a clone of lymphocytes just like itself. These lymphocytes then secrete their antibody, destroying the pathogen (Figure B8.16).

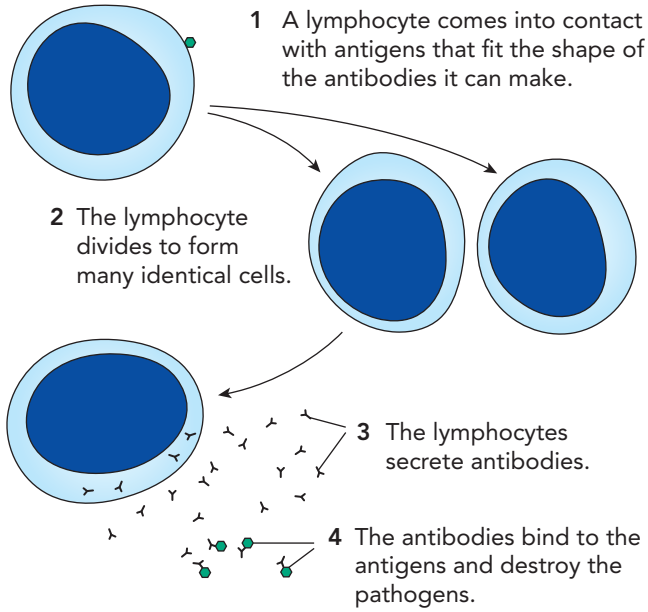

Figure B8.16: How lymphocytes respond to a pathogen.

This takes time. It may take a while for the 'right' lymphocyte to recognise the pathogen, and then a few days more for it to produce enough identical lymphocytes to make enough antibodies to kill the pathogen. In the meantime, the pathogen breeds, making you ill. Eventually, however, the lymphocytes, antibodies and phagocytes usually manage to destroy the pathogen, and you get better.

Lymphocytes are a very important part of your immune system. The way in which they respond to pathogens, by producing antibodies, is called the **immune response**.

KEY WORDS

immune response: the reaction of the body to the presence of an antigen; it involves the production of antibodies.

Memory cells

When a lymphocyte makes copies of itself (clones), not all of the new cells make antibodies. Some of them simply remain in the blood and other parts of the body, where they can live for a very long time. They are called **memory cells**.

If the same kind of pathogen gets into the body again, these memory cells will be ready and waiting for them.

KEY WORDS

memory cells: long-lived cells produced by the division of lymphocytes that have contacted their antigen; memory cells are able to respond quickly to subsequent contact with the same antigen.

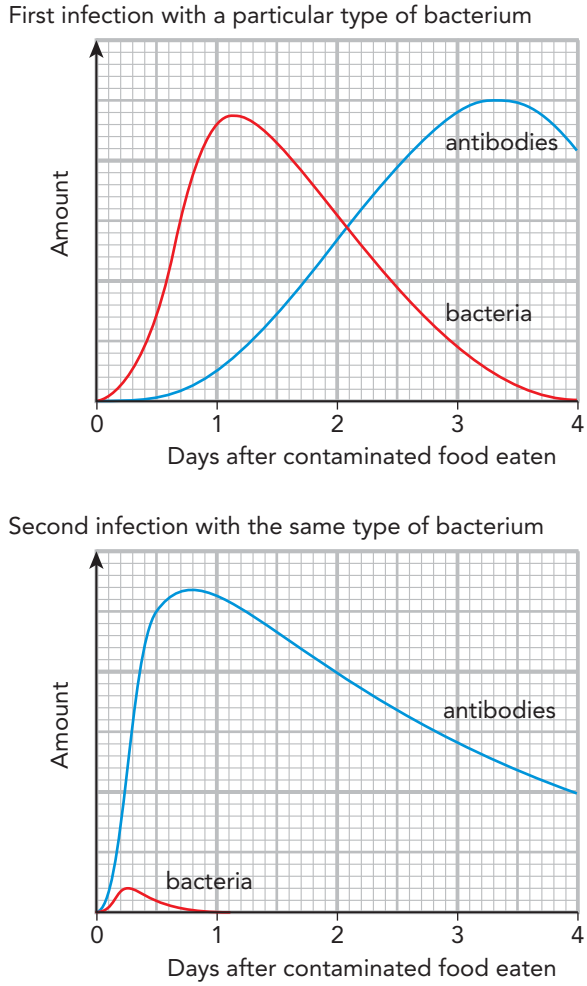

Figure B8.17: Changes in the amount of antibodies and number of bacteria after a first and second infection.

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They will be able to make enough antibodies, very quickly, to kill the pathogens before they have time to produce a large population and do any harm. The person has become immune to that type of pathogen.

Figure B8.17 shows how numbers of bacteria and antibodies in the body change after infection with a pathogen that your immune system has not met before, and when it infects you a second time.

Questions

B8.07 Explain the difference between an antigen and an antibody.

B8.08 A learner wrote that antibodies are the same shape as their specific antigens. What is wrong with that statement?

B8.09 Look at the first graph in Figure B8.17.

a Infection happens at time 0. Explain why the number of antibodies does not begin to rise until some hours after this.

b Describe and explain what happens to the number of bacteria over the four-day period.

B8.10 Look at the second graph in Figure B8.17.

Describe and explain what happens to the number of bacteria the second time a person comes into contact with the bacteria.

B8.11 Predict and explain what would happen if the person was infected with a different kind of bacterium, after an immune response like the one in Figure B8.17.

PEER ASSESSMENT

Exchange your answer to Question B8.11 with a partner.

Has your partner made a clear *prediction* about what would happen?

Have they given a clear *explanation* of what they predict would happen?

Give feedback to your partner about how well you think they have done this. Listen to their feedback on your answer, and make changes to your answer if necessary.

Vaccination

In most countries, children are given vaccinations at various ages as they grow up. This is to immunise children against diseases caused by pathogens. Adults can also be given vaccinations if they are at risk of getting particular diseases.

A **vaccine** may contain weakened or dead viruses or bacteria that normally cause disease. Some vaccines do not contain complete viruses or bacteria, but only their antigens.

When the weakened pathogens or their antigens are introduced into the body, they are recognised by the lymphocytes that can make antibodies that have a complementary shape to their antigens. These lymphocytes multiply and produce antibodies just as they would after a 'real' infection. They also make memory cells, which give long-term immunity. So, if the 'normal' viruses or bacteria get into the body one day, they will be attacked and destroyed immediately.

Some diseases require two vaccinations to provide really good, long-lasting immunity. After the first dose, the body makes enough antibodies and memory cells to provide partial protection against the pathogen. A second vaccination given a few weeks afterwards, sometimes called a booster, stimulates the lymphocytes and memory cells to make even more antibodies and even more memory cells.

Active immunity

A person has **active immunity** to a disease if their body has made its own antibodies that protect against that disease. You can develop active immunity by:

- having the disease and recovering from it
- being vaccinated.

KEY WORDS

vaccine: a harmless preparation of dead or inactivated pathogens that is injected into the body to induce an immune response.

active immunity: long-term defence against a pathogen by antibody production in the body.

The body also makes memory cells. These memory cells can last in the body for many years. Therefore, active immunity can last a long time – sometimes an entire lifetime.
The memory cells that were made during the infection, or after the vaccination, can spring into action at a moment's notice to make antibodies and stop an invading pathogen in its tracks.

Controlling disease by vaccination

Smallpox is a serious, often fatal, disease caused by a virus. It is transmitted by direct contact. If a person survives smallpox, they are often left with badly scarred skin, and may be made blind.

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In 1956, the World Health Organization (WHO) began a campaign to try to completely eradicate smallpox. They wanted to make the smallpox virus extinct. They set up systems to get as many people as possible, all over the world, vaccinated against smallpox. The campaign was a success. More than 80% of people in the world who were at risk from the disease were vaccinated. The very last case of smallpox happened in 1977, in Somalia. By 1980, three years had gone by with no more cases, and the WHO were able to declare that smallpox had been eradicated.

Currently, attempts are being made to eradicate some other very serious diseases caused by viruses. One of these is poliomyelitis (polio for short) (Figure B8.18). Polio can infect children, and usually leaves them with permanent paralysis of parts of their bodies. Eradicating this virus is proving difficult, as people in some countries are resisting efforts to vaccinate children. Polio is now very rare in most parts of the world, but cases are still occurring in a small number of countries.

Figure B8.18: A child being vaccinated for polio. The polio vaccine is unusual because it can be given by mouth – no injection is needed.

The control of many other serious infectious diseases relies on vaccination of children. For example, we saw in the Science in context at the start of this chapter that, in most countries, children are vaccinated against measles. Measles is spread by airborne droplets. It causes a skin rash and fever, and there can be very severe complications, such as blindness and brain damage.

Vaccinating children against measles protects not only the children that are vaccinated, but also those that are not. This is sometimes called 'herd immunity'. This means vaccinating enough individuals protects the whole 'herd' of people, even the ones who have not been vaccinated. 'Herd immunity' works because there are fewer places for the measles viruses to replicate. They can only do so if they enter the body of an unvaccinated person.

ACTIVITY B8.03

Vaccinations in your country

Work with a partner, or in a small group.

Use the internet to find out what vaccinations are given to young children in your country.

- Do any of the vaccinations need to be given more than once, to provide good immunity?
- At what ages are the vaccinations given?

Questions

B8.12 Outline *two* ways in which active immunity can be gained.

B8.13 Explain how vaccination can help to control the spread of a transmissible disease.

COVID-19

In December 2019, a new infection was detected. Scientists discovered that the pathogen that caused it was a new virus, which they named SARS-CoV-2. This stands for Severe Acute Respiratory Syndrome Coronavirus 2.

Coronaviruses are spherical viruses (Figure B8.19), with protein spikes sticking out. These spikes help the virus to attach to human cells. We already live with many different coronaviruses, which cause colds and flu. But this one is different because the illness it causes can often be very severe, and even fatal.

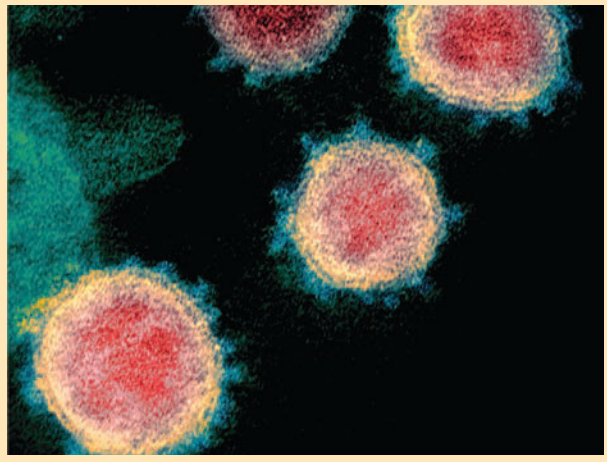

Figure B8.19: This electron micrograph shows four SARS-CoV-2 coronavirus particles. The protein coat with its spikes has been artificially coloured blue in this image, magnified ×200 000.

(Continued)

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The disease caused by SARS-CoV-2 has become named COVID-19. You may like to try to work out what the letters and number in that name refer to.

Learning about COVID-19

It took a little while for scientists to learn important facts about COVID-19. In particular, people needed to know how it is transmitted. This would help countries to plan how they could reduce the transmission. They also needed to find out how the virus affects the body, which would help to find ways to treat the disease.

- The virus is very easily transmitted from one person to another. It can be passed on in droplets, when a person coughs, sneezes or talks. It can remain on a surface – such as a door handle – for several days, and then get into another person's respiratory system if they touch the surface and then their mouth. Because the virus spreads so easily, it quickly caused a pandemic.
  A pandemic is a disease that is present all over the world.
- The virus can even be transmitted from a person who does not have any symptoms. People can be completely unaware that they could be passing the virus on.
- In most people, the virus causes only mild symptoms. But in others, the lungs can be so badly affected that the person has great difficulty breathing. Even with excellent medical treatment, some of these people die.

Scientists from many different countries worked together to discover all they could about the virus: how it is transmitted, what it does to the body and how to stop it. Medical staff across the globe focused their attention on finding ways to treat people who were suffering severe symptoms. Mathematical modellers used the information that different countries were providing – about numbers of people infected with the virus, how many of them were ill enough to be admitted to hospital, how many of them died – and tried to predict what would happen next, and how different strategies might help to keep the numbers of infected and seriously ill people to a minimum.

Many countries asked people to stay at home and not travel. Tests were developed to find out who had the virus, and some governments asked people who tested positive to isolate themselves for 14 days. In many countries, people who did go out were asked to wear masks (Figure B8.20).

ACTIVITY B8.04

Researching COVID-19

COVID-19 is a new disease. You are going to research the current understanding of this disease, and how people are affected by it.

In your group, choose *one* of these topics to research. If you are not studying the Supplement, then Topic 1 is the best choice. Select websites carefully, ensuring that they are providing you with good scientific information. Use your findings to contribute to a display to put on the wall of the laboratory or your classroom.

Topic 1 *How did your country respond to the fight against COVID-19?*

What did your country do to try to stop this disease spreading when it first appeared? How does this compare with what other countries did? Why did different countries take different steps? Which worked best? How can we use this information to make better decisions if another pandemic arises in future?

Topic 2 *What does the virus do in the body?*

How does the virus infect cells? How does the immune system respond to infection with this virus? What have scientists learnt about why some people are more likely to become very ill than others? What treatments have proved to be most effective, and why?

Topic 3 *A vaccine against COVID-19*

Producing and testing vaccines was done much more quickly than usual – how was this achieved? Have any vaccines proved to be successful? How do the vaccines work? Who is able to be vaccinated? How does this affect the lives of people in different countries of the world?

Figure B8.20: Research shows that wearing a mask not only reduces the risk of passing a virus to someone else, but also reduces the person's risk of inhaling it themselves.

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PROJECT B8.01 FINDING A VACCINE FOR MALARIA

Malaria is a serious disease that kills thousands of people each year, mostly children. The first malaria vaccine to be used on a widespread scale was launched in Kenya, Ghana and Malawi in 2019.

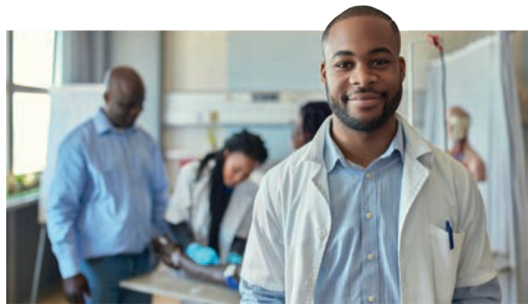
You are going to help to write a short play about the introduction of this vaccine, and then perhaps take part in the play.

First, do some research about the first vaccine that was used in 2019. You could search on the following websites to begin with, but do look for others as well:

- World Health Organization website: search for malaria vaccine
- History of Vaccines website: search for malaria
- Zero Malaria Africa website.

When you feel that you have collected enough information, begin to think about your play.

It could involve characters like some of the following people:

Scientists trying to develop a malaria vaccine or who have developed one that is now going to be used on a large scale for the first time.	
A philanthropist who is giving money to support the production and use of the malaria vaccine.	
Doctors who will be involved in the malaria vaccine campaign.	

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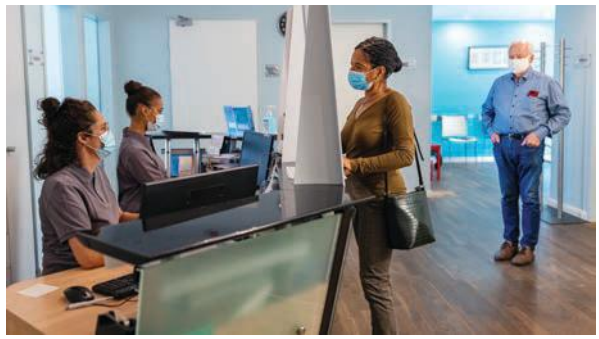
CONTINUED

Health workers who will be administering the vaccines.	
Parents who are wondering whether to let their child be given the vaccine.	
Children and/or adults who are going to be given the vaccine.	
Anyone else who might be involved in the project.	

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SUMMARY

Transmissible diseases are caused by pathogens, which can be passed from one host to another.
Pathogens can be transmitted through direct contact with blood or other body fluids, or indirectly through contaminated surfaces, food, from animals or through the air.
The body has defences to prevent the entry of pathogens, including skin, hairs in the nose, mucus and stomach acid. White blood cells destroy pathogens that get through these defences and enter the body.
We can control the spread of disease with clean water supplies, hygienic food preparation, good personal hygiene, safe waste disposal, and sewage treatment.
Each pathogen has its own antigens, which have specific shapes.
Lymphocytes produce antibodies, which are proteins with specific shapes that are complementary to specific antigens. Antibodies bind with their antigens and either destroy the pathogen directly or make it easier for phagocytes to destroy the pathogen.
Lymphocytes that have made contact with their antigen divide to form clones of memory cells. These remain in the body for long periods of time and can quickly respond to entry of pathogens with the same antigen at a later date.
The production of antibodies from the body's own lymphocytes leads to active immunity. This is long-lasting.
The production of memory cells from the body's own lymphocytes leads to active immunity.
Active immunity can result from having a disease and recovering from it, or from vaccination.
Vaccination of a high percentage of a population helps to stop the spread of disease, because there are only a few unvaccinated hosts in which a pathogen can reproduce.

PRACTICE QUESTIONS

1 **Identify** the correct term for a microorganism that causes disease.

A antibody
B host
C pathogen
D vector [1]

2 Identify a function of mucus in the passages leading to the lungs.

A making it easy for air to move in and out of the lungs
B providing a low pH that kills pathogens
C secreting enzymes to kill bacteria
D trapping microorganisms before they reach the lungs [1]

COMMAND WORD

identify: name/select/recognise.

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CONTINUED

3 a Complete the sentences about diseases. Choose words from the list.

bacteria enzymes host mucus pathogens viruses

All transmissible diseases are caused by _____, which are passed from one _____ to another.

The lining of the respiratory passages helps to prevent this from happening by producing _____. **[3]**

b **Describe** how the body defences help to prevent bacteria entering:

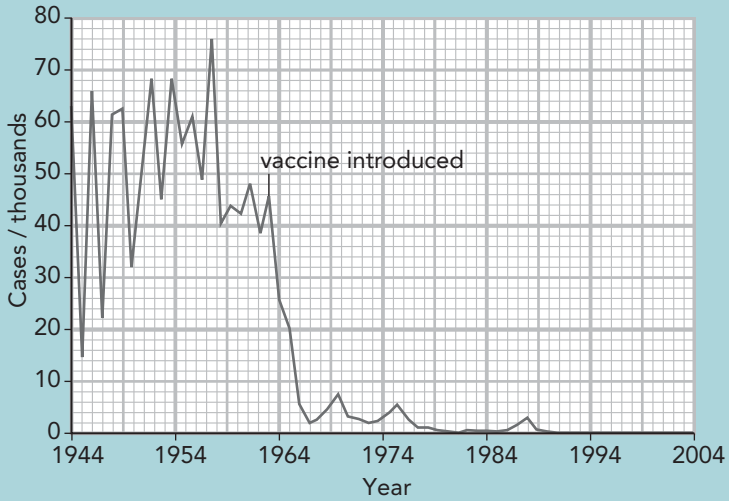
i through the skin **[2]**

ii in food. **[3]**

[Total: 8]

4 a **Explain** how vaccination produces active immunity in a child. **[5]**

b The graph shows the number of cases of measles in the USA between 1944 and 2004. Measles is caused by a virus. Vaccination for measles was introduced in the USA in 1963.



i Describe how the number of cases of measles in the USA changed between 1945 and 1958. **[3]**

ii Describe *and* explain the effect of the introduction of vaccination. **[4]**

[Total: 12]

COMMAND WORDS

describe: state the points of a topic/give characteristics and main features.

explain: set out purposes or reasons/make the relationships between things clear/say why and/or how and support with relevant evidence.

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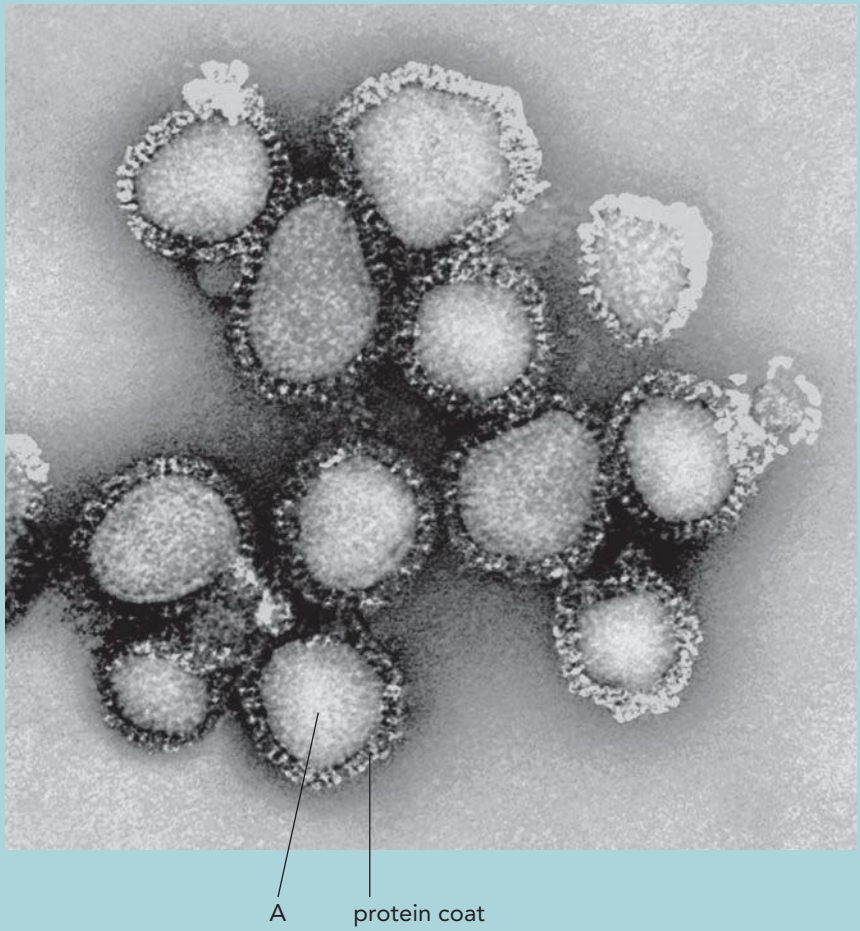
CONTINUED

5 The electron micrograph shows a group of influenza viruses.



a Identify the part of the virus labelled **A**. **[1]**

b New strains of the influenza virus frequently occur. The new strains have different proteins in their coats.

Explain why a person who has recovered from influenza in one year may not be immune to influenza in the future. **[5]**

[Total: 6]

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SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
explain what a pathogen is	B8.01			
describe how pathogens can be transmitted through direct contact, or indirectly	B8.01			
describe how the skin, hairs in the nose, mucus, stomach acid and white blood cells help to defend against pathogens	B8.01			
explain the importance of clean water, hygienic food preparation, personal hygiene, waste disposal and sewage treatment in controlling the spread of disease	B8.01			
explain what an antigen is, and state that each pathogen has its own antigens with a specific shape	B8.02			
describe antibodies as proteins secreted by lymphocytes	B8.02			
describe how antibodies bind to specific antigens with a complementary shape	B8.02			
outline how antibodies destroy pathogens, or help phagocytes to destroy them	B8.02			
explain what active immunity is, and how it is acquired by an infection or vaccination	B8.02			
describe how memory cells are produced, and what they do	B8.02			
outline how vaccination can provide long-term immunity	B8.02			
explain how vaccination can help to control the spread of transmissible diseases.	B8.02			

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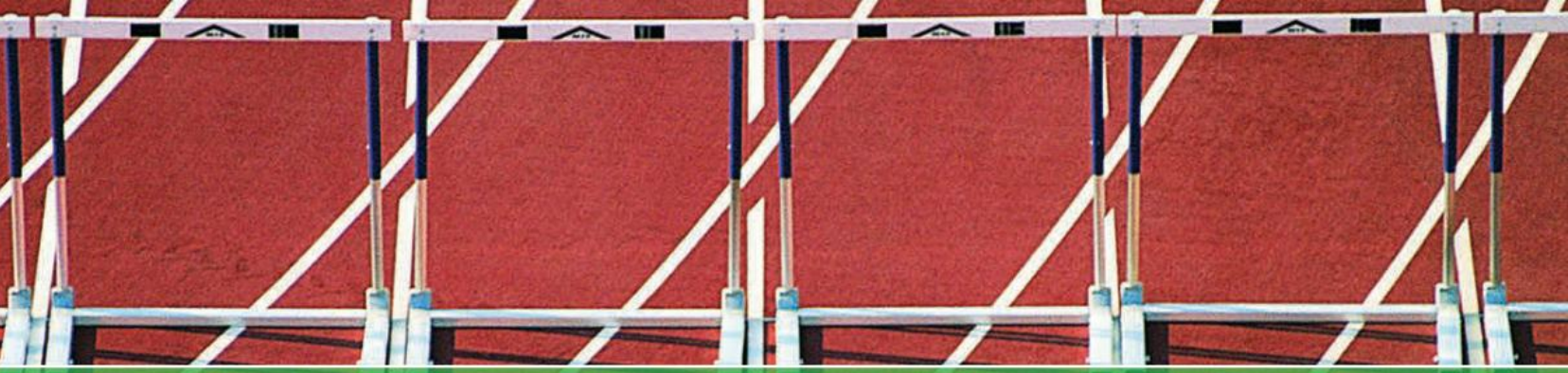

B9

Gas exchange and respiration

All learners study some content in this chapter

IN THIS CHAPTER YOU WILL:

- describe how gas exchange happens in the lungs, and the features of gas exchange surfaces
- investigate the differences in composition between inspired and expired air
- explain the differences in composition between inspired and expired air
- explain how activity affects breathing rate
- find out how the body uses energy, and how aerobic and anaerobic respiration supply this energy
- learn the equations for aerobic respiration and anaerobic respiration
- learn about lactic acid and oxygen debt.

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BEFORE YOU START

- Sit quietly. Rest one hand against your sternum (breastbone) like the girl in Figure B9.01. Think about the breathing movements you can feel.
- Now stand up and take four or five steps on the spot. Feel your breathing movements again.
- What happened? Why did this happen?

SCIENCE IN CONTEXT B9.01

Sleep apnoea

Most of the time, we breathe regularly without even thinking about it. If you count your breathing movements, perhaps feeling the movements of your thorax (chest) as you breathe (Figure B9.01), you will probably find that you breathe in and out between 12 and 22 times each minute. Breathing moves air into and out of the lungs, providing oxygen that can be transported to all the cells in the body in the blood.

Breathing is an automatic process, which happens even when we are asleep. But for some people, sleeping greatly disrupts their pattern of breathing. They seem to hold their breath for a long time, and then suddenly breathe in – sometimes with a snorting, gasping noise. People often wake themselves up when they do this. This condition is called sleep apnoea. If it is severe, it can cause health problems.

A person with severe sleep apnoea can be helped by using a small machine to pump air into a mask that they wear over the mouth or nose while asleep. This helps to keep their breathing more regular, so that they can get a better night's sleep. Serious sleep apnoea is more common in people who are very overweight, so losing weight can also help. It may also be helpful if they sleep on their side, rather than on their back. Stopping smoking is also a good idea.

Figure B9.01: You can feel your breathing movements by resting your hand just below the collarbone.

Discussion question

1 Breathing happens automatically, but we can also at least partly control it consciously. In contrast, we cannot control our heartbeat consciously. Can you suggest any reasons for these two processes being different in this respect?

B9.01 Gas exchange in humans

The human breathing system

Animals and plants need oxygen to survive. They get their oxygen directly from their surroundings – either from the air for terrestrial (land-living) organisms or from oxygen dissolved in water for aquatic (water-living) ones.

When an organism breathes, the **gas exchange** system gets oxygen into the blood and removes carbon dioxide. The areas in an organism where the oxygen enters and carbon dioxide leaves are called **gas exchange surfaces**.

Figure B9.02 shows some of the main structures which are involved in gas exchange in a human.

KEY WORDS

gas exchange: the diffusion of oxygen and carbon dioxide into and out of an organism's body.

gas exchange surface: a part of the body where gas exchange between the body and the environment takes place.

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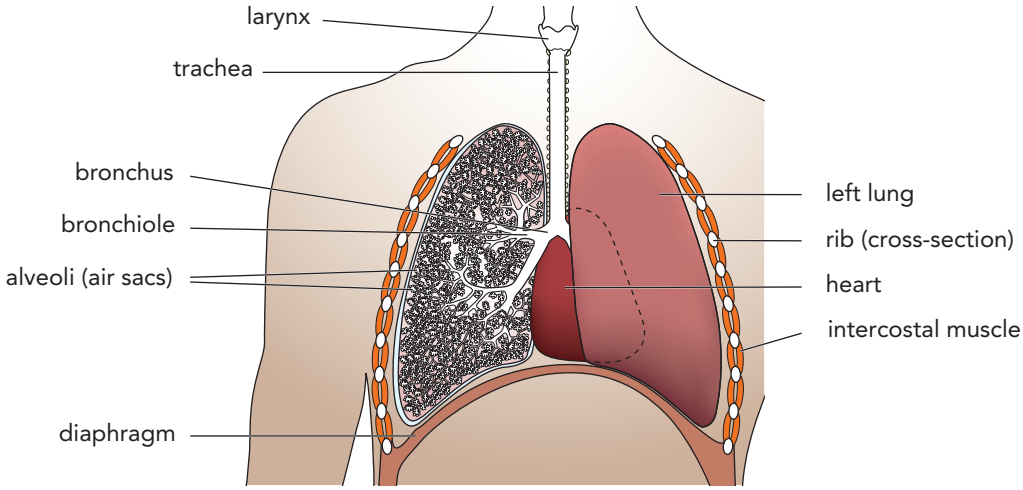

Figure B9.02: The human gas exchange system.

Trachea

From the nose or mouth, the air then passes into the windpipe or trachea. Just below the epiglottis is the voice box or larynx. This contains the vocal cords. The vocal cords can be tightened by muscles so that they make sounds when air passes over them.

Bronchi

The trachea goes down through the neck and into the **thorax**. The thorax is the upper part of your body from the neck down to the bottom of the ribs and diaphragm. In the thorax, the trachea divides into two. The two branches are called the right and left bronchi (singular: **bronchus**). One bronchus goes to each lung and then branches out into smaller tubes called **bronchioles**.

Lungs

The most obvious parts of the human gas exchange system are the two lungs. Each lung is filled with many tiny air spaces called air sacs or **alveoli**. It is here that oxygen diffuses into the blood. Because they are so full of air spaces, lungs feel very light and spongy to touch. The lungs are supplied with air through the windpipe or trachea.

Alveoli

There are many tiny air sacs or alveoli at the end of each bronchiole (Figure B9.03). This is where gas exchange takes place.

Tiny capillaries are closely wrapped around the outside of the alveoli. Oxygen diffuses across the walls of the alveoli into the blood. Carbon dioxide diffuses the other way (Figure B9.04).

KEY WORDS

thorax: the chest; the part of the body from the neck down to the diaphragm.

bronchus: one of the two tubes that takes air from the trachea into the lungs.

bronchiole: a small tube that takes air from a bronchus to every part of the lungs.

alveoli: tiny air-filled sacs in the lungs where gas exchange takes place.

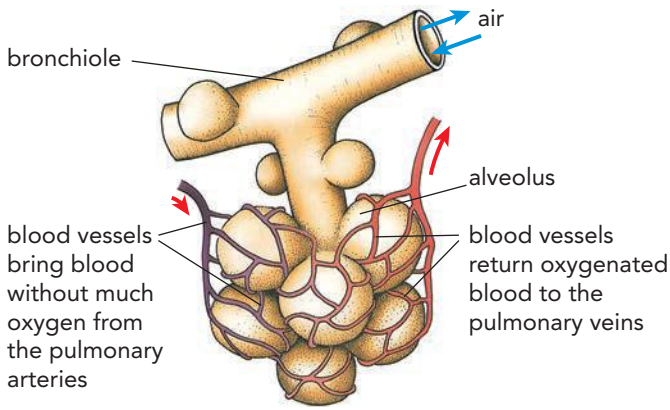

Figure B9.03: Alveoli in the lungs, and the blood vessels that are associated with them.

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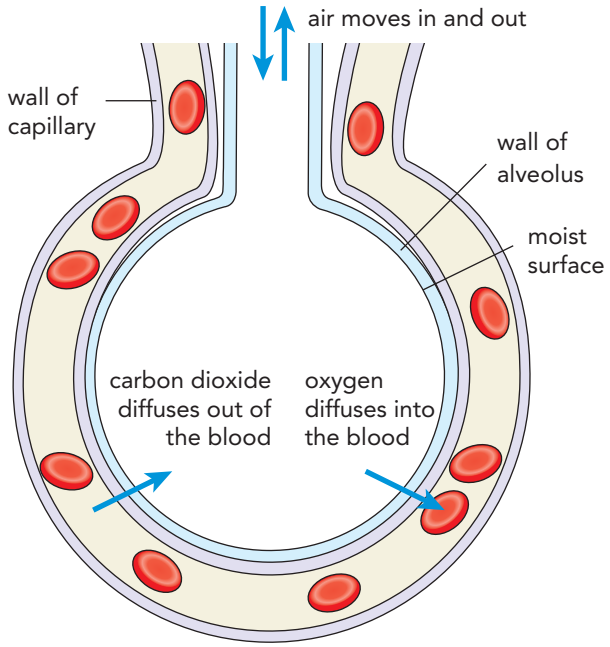

Figure B9.04: Gas exchange across the wall of an alveolus.

The walls of the alveoli have several features which make them an efficient gas exchange surface:

- They are permeable, so that oxygen and carbon dioxide can move easily through them.
- They are very thin. They are only one cell thick. The capillary walls are also only one cell thick. An oxygen molecule only has to diffuse across this small thickness to get into the blood.
- They have an excellent transport system. Blood is constantly pumped to the lungs along the pulmonary artery. This branches into thousands of capillaries which take blood to all parts of the lungs. Carbon dioxide in the blood can diffuse out into the air spaces in the alveoli and oxygen can diffuse into the blood. The blood is then taken back to the heart in the pulmonary vein, ready to be pumped to the rest of the body.
- They have a large surface area. In fact, the surface area is enormous. The total surface area of all the alveoli in your lungs is over 100 m^2.
- They have a good supply of oxygen. Your breathing movements keep your lungs well supplied with oxygen. This is called **ventilation**.

Intercostal muscles and diaphragm

To make air move in and out of the lungs, you must change the volume of your thorax. First, you make it large so that air is sucked in. Then you make it smaller again so that air is squeezed out. This is called **breathing**.

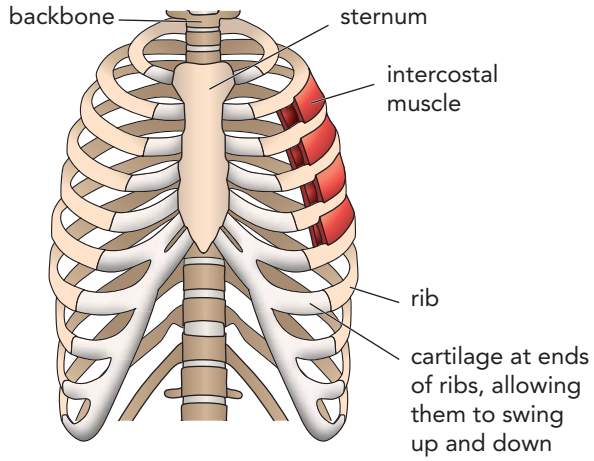

Figure B9.05: The rib cage and intercostal muscles.

Muscles in two parts of the body help you to breathe. Some of these muscles, called the **intercostal muscles**, are between the ribs (Figure B9.05). The others are in the **diaphragm**. The diaphragm is a large sheet of muscle and elastic tissue which stretches across your body, underneath the lungs and heart.

KEY WORDS

ventilation: the movement of air into and out of the lungs, by breathing movements.

breathing: using the muscles in the diaphragm, and the intercostal muscles, to change the volume of the thorax so that air is drawn into and pushed out of the lungs.

intercostal muscles: muscles between the ribs, which raise and lower the rib cage when they contract and relax.

diaphragm: a muscle that separates the chest cavity from the abdominal cavity in mammals; it helps with breathing.

Questions

B9.01 List, in order, all of the structures that a molecule of oxygen passes through as it moves from the air, through the nose or mouth, down into the lungs, and into the blood.

B9.02 In Figure B9.04, look carefully at the arrows showing the movement of oxygen into the blood, and carbon dioxide out of the blood. Apart from going in different directions, what other difference can you see between them? Explain this difference.

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B9.03 Look at Figure B9.04 again. Some of the movement indicated by the arrows is mass flow, where a lot of air all moves in the same direction. Some of the movement is by diffusion, where individual molecules move randomly. Which arrows represent which type of movement?

B9.04 People who smoke cigarettes often develop an illness called emphysema, where the walls of the alveoli break down. Instead of having millions of tiny air spaces in their lungs, they have fewer larger ones. Predict how this might affect the person's ability to do exercise. Explain your prediction.

Comparing inspired air and expired air

Table B9.01 summarises the differences between the composition of inspired air and expired air.

The air that we breathe in usually has an oxygen content of about 20–21%. There is less oxygen in the air that we breathe out, because cells in the body use oxygen in respiration.

Component	Percentage in inspired air	Percentage in expired air
oxygen	21	16
carbon dioxide	0.04	4
water vapour	variable	usually very high

Table B9.01: A comparison of inspired air and expired air.

However, expired air does still contain a significant amount of oxygen, usually about 16%. The main reason for this is that our expired air mixes with normal air in the bronchi and trachea, so that what we actually breathe out is a mixture of the air in the alveoli, and atmospheric air.

The air we breathe in contains only a very small percentage of carbon dioxide, usually about 0.04%. Body cells produce carbon dioxide in aerobic respiration, and this carbon dioxide diffuses out of the blood and into the alveoli. Extra carbon dioxide is therefore present in the air that we breathe out, increasing its concentration to about 4%.

EXPERIMENTAL SKILLS B9.01

Investigating the difference in composition between inspired and expired air

In this investigation, you will use limewater to compare how much carbon dioxide there is in the air you breathe in and the air you breathe out. You will practise observing carefully, and then use your observations to draw a conclusion.

You will need:

- the apparatus shown in Figure B9.06.

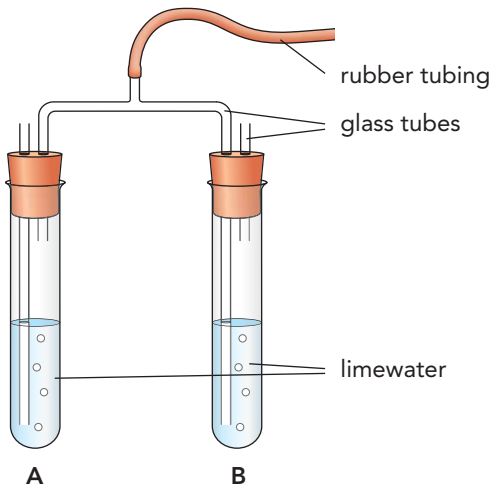

Figure B9.06: Apparatus for comparing the carbon dioxide concentration in inspired and expired air.

Safety

Limewater is an irritant. Do not get it in your mouth. Wear safety goggles when breathing in and out through the tubing. Make sure that you do not suck hard through the rubber tubing.

Take care that the rubber tubing is really clean before you put your mouth over it. Use a new piece of tubing for each person who uses the apparatus.

Method

1. Look carefully at the apparatus – especially at the lengths of the glass tubes. When someone breathes gently into the rubber tubing, in which test-tube do you predict bubbles will appear?
2. Breathe gently into and out of the rubber tubing. Take care not to suck too hard – you want to make bubbles appear in the limewater, not suck limewater into your mouth. Keep doing this until the limewater in one of the test-tubes becomes cloudy.
3. Continue breathing in and out for a while. You may find that the limewater in the other test-tube also becomes cloudy.

Questions

1. Explain why bubbles appeared in different test-tubes when you breathed in and when you breathed out.
2. Explain why the limewater went cloudy more quickly in one of the test-tubes.

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Questions

B9.05 Suggest why the quantity of water vapour in expired air is always high.

B9.06 Nitrogen is soluble in water, and molecules of nitrogen gas can pass easily through cell membranes. Body cells cannot use nitrogen gas. Inspired air contains about 79% nitrogen. Predict the percentage of nitrogen in expired air and explain your prediction.

Exercise and breathing rate

EXPERIMENTAL SKILLS B9.02

Investigating the effect of physical activity on rate and depth of breathing

In this experiment, you will investigate how exercise affects your breathing. You will plan your own experiment, using the experience you gained when you did Experimental skills B7.03 Investigating the effect of physical activity on heart rate.

This investigation gives you practice in planning an experiment where you change one variable, measure another and try to keep other important variables the same.

You will need:

- a timer.

Safety

If you are worried that doing exercise might make you ill, do not do it! You can measure someone else's breathing rate instead.

Before you start

Practise measuring breathing rate and depth. Work with a partner. Decide how you will count how many breaths you take per minute. For breathing depth, you may need to just observe any changes, rather than trying to measure them. Make a firm decision about how you will do this.

Method

1. Make a plan of what you will do. Think about how you will change your independent variable (activity). You may find it helpful to look at the instructions for Experimental skills B7.03 Investigating the effect of physical activity on heart rate. Or, think about how you did that investigation.
2. Construct a results table.

CONTINUED: B9.02

3. Do your experiment and record your results in your table. Be prepared to make changes to your original plan, if you realise that this would improve your experiment.

Questions

1. Use your results to draw a line graph. Put time in minutes on the *x*-axis. Put breathing rate in breaths per minute on the *y*-axis. Mark on the *x*-axis where exercise began and ended. Use a ruler to join the points with straight lines.
2. Use your table or graph to describe, in words, how exercise affected breathing rate.
3. Evaluate the reliability of your results. Do you think you would get the same results if you did your experiment again tomorrow? Explain why you think this.

Explaining the effects of exercise on breathing rate

As you will read later in this chapter, all the cells in your body need oxygen for respiration and all of this oxygen is supplied by the lungs. The oxygen is carried by the blood to every part of the body.

Sometimes, cells may need a lot of oxygen very quickly. Imagine you are running in a race. The muscles in your legs contract much harder and more frequently than usual, so they require more energy. The cells in the muscles combine oxygen with glucose as fast as they can, to release extra energy for muscle contraction.

A lot of oxygen is needed to work as hard as this. You breathe deeper and faster to get more oxygen into your blood. Your heart beats faster to get the oxygen to the leg muscles as quickly as possible.

Eventually a limit is reached. The heart and lungs cannot supply oxygen to the muscles any faster. But the muscles continue to contract quickly, requiring more energy. How can that extra energy be found?

Extra energy can be provided by **anaerobic respiration**.

KEY WORDS

anaerobic respiration: chemical reactions in cells that break down nutrient molecules to release energy, without using oxygen.

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The muscle cells continue to respire aerobically with the oxygen they have, but they also break down some glucose without combining it with oxygen.

glucose → lactic acid + energy

As you will read later, anaerobic respiration does not release very much energy, but a little extra might make all the difference.

When you stop running, you will have quite a lot of lactic acid in your muscles and your blood. This lactic acid must be broken down by combining it with oxygen in the liver. This is done by aerobic respiration in the liver cells. So, even though you no longer need extra energy, you continue to breathe faster and more deeply than normal, and your heart rate continues to be high. You are taking in and transporting extra oxygen to break down the lactic acid. The faster heart rate also helps to transport lactic acid as quickly as possible from the muscles to the liver.

While you were running, you built up an **oxygen debt**. You 'borrowed' some extra energy, without 'paying' for it with oxygen. Now, as the lactic acid is combined with oxygen, you are paying off the debt. Not until all the lactic acid has been used up, do your breathing rate and heart rate return to normal (Figure B9.07).

Figure B9.07: Runners in a 4 × 400 m relay race use anaerobic respiration, as well as aerobic respiration, to provide energy to their muscles.

KEY WORDS

oxygen debt: extra oxygen that is needed after anaerobic respiration has taken place, in order to break down the lactic acid produced.

Control of breathing rate

The rate at which your breathing muscles work – and therefore your breathing rate – is controlled by the brain. The brain constantly monitors the pH of the blood that flows through it. If there is a lot of carbon dioxide or lactic acid in the blood, this causes the pH to fall. When the brain senses this, it sends nerve impulses to the diaphragm and the intercostal muscles. This stimulates them to contract harder and more often. The result is a faster breathing rate and deeper breaths.

B9.02 Respiration

Using energy

Every living cell needs energy. In humans, our cells need energy for:

- contracting muscles, so that we can move parts of the body
- making protein molecules (protein synthesis) by linking together amino acids into long chains
- cell division, so that we can repair damaged tissues and can grow
- active transport, so that we can move substances across cell membranes up their concentration gradients
- growth, by building new cells which can then divide to form new cells
- producing heat inside the body, to keep the body temperature constant even if the environment is cold
- transmitting nerve impulses, so that we can transfer information quickly from one part of the body to another.

All of this energy comes from the food that we eat. The food is digested – that is, broken down into smaller molecules – which are absorbed from the small intestine into the blood. The blood transports the nutrients to all the cells in the body. The cells take up the nutrients that they need.

The main nutrient used to provide energy in cells is glucose. Glucose contains a lot of chemical energy. In order to make use of this energy, cells have to break down the glucose molecules and release the energy from them. They do this in a series of metabolic reactions called respiration. Like all metabolic reactions, respiration involves the action of enzymes.

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Aerobic respiration

Most of the time, our cells release energy from glucose by combining it with oxygen. This is called aerobic respiration.

This happens in a series of small steps, each one controlled by enzymes. Most of the steps in aerobic respiration take place inside mitochondria.

We can summarise the reactions of aerobic respiration as a word equation:

glucose + oxygen → carbon dioxide + water

The balanced chemical equation is:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$$

Anaerobic respiration

It is possible to release energy from glucose without using oxygen. It is not such an efficient process as aerobic respiration and not much energy is released per glucose molecule. This is called anaerobic respiration ('an' means without). Anaerobic respiration happens in the cytoplasm of a cell, not in mitochondria.

Some of the cells in your body, particularly muscle cells, can also respire anaerobically for a short time. When they do this, they make lactic acid. No carbon dioxide is produced. This happens when you do vigorous exercise, and your lungs and heart cannot supply oxygen to your muscles as quickly as they are using it. The muscle cells are able to release at least some energy from glucose without using oxygen, just to keep them going until oxygen is available again.

glucose → lactic acid

Table B9.02 compares aerobic and anaerobic respiration.

REFLECTION

There are several equations to learn here. You have already learnt the equation for photosynthesis in Chapter B5.

How will you try to remember all of these equations, and not get them mixed up?

Aerobic respiration	Anaerobic respiration
involves chemical reactions in cells that break down glucose to release energy	involves chemical reactions in cells that break down glucose to release energy
uses oxygen	does not use oxygen
no alcohol or lactic acid made	lactic acid (in animals) is made
large amount of energy released from each molecule of glucose	much less energy released from each molecule of glucose
carbon dioxide made	carbon dioxide is not made by animals

Table B9.02: A comparison of aerobic and anaerobic respiration.

Questions

B9.07 Look at the equation for aerobic respiration (either the word equation, or the balanced equation). How does this compare with the equation for photosynthesis, which you learnt in Chapter B5?

B9.08 In which cells in your body does respiration happen?

B9.09 In respiration, energy is released from glucose. Think back to your earlier work, and explain how the energy became incorporated into the glucose molecules.

ACTIVITY B9.01

Explaining the meanings of terms

Many people use the words *breathing*, *respiration* and *gas exchange* as though they mean the same thing.

Work in a small group to discuss the meaning of these three terms. Try to write a short, clear description of each one, which makes clear the differences between them.

Share your ideas with other groups. Use the best ideas from all the groups in your class to write a really clear description that you think will help everyone to use the words correctly.

Peer assessment

Ask the other groups for some feedback about your first descriptions.

What do they suggest you do next time to make your description more informative?

How could your description be better presented next time to make it clearer for the group to understand?

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PROJECT B9.01 SCIENTIFIC AND EVERYDAY USAGE OF TERMS

The terms *respiration* and *breathing* are often used in everyday life in ways that do not always match their scientific meaning. For example, we talk about 'artificial respiration'. We say that frogs 'breathe' through their skin. Neither of these is the correct usage of the words in their scientific sense.

You are going to explore this issue, and contribute to a display about the scientific meaning, and the everyday usage, of these two words.

Work in a group of three for this project.

Choose one of these three issues to investigate. If possible, different groups should research different issues, so that you can combine your findings to make one display for the whole class.

Before you begin to investigate your chosen issue, make sure that you are absolutely certain about the scientific meanings of *respiration* and *breathing*.

Issue 1: Do all languages have different words for respiration and breathing?

This would be a good choice for a group containing people who can speak different languages. You could also use the internet to search for these words in other languages.

Issue 2: Is the word respiration always used in its correct scientific sense?

Here are some suggestions for how you might investigate this issue.

- Construct some questions or conversation openers that you could use to talk to people, and listen to how they use this word. You could perhaps make a recording of your questions and their answers.
- Look at magazines, newspapers and social media to find examples of this word. Remember to look for other forms of the word – respire, respires, respired and respiring as well as respiration.

Issue 3: Is the word *breathing* always used in its correct scientific sense?

You could use the same approach as described for Issue 2. Again, remember to look for different forms of the word – breathe, breathes and breathed as well as breathing.

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SUMMARY

The place where oxygen enters an organism's body and carbon dioxide leaves is called the gas exchange surface. In terrestrial animals, these surfaces have a large surface area, a thin surface, a good blood supply and good ventilation with air.
In humans, the gas exchange surface is the alveoli in the lungs. Air moves to them through the trachea, bronchi and bronchioles.
Inspired air contains more oxygen and less carbon dioxide than expired air.
Physical activity causes the rate and depth of breathing to increase, in order to supply extra oxygen to muscles.
The depth and rate of breathing are controlled by the brain, which detects a decrease in the pH of the blood when it contains more carbon dioxide or lactic acid than usual. During exercise, faster aerobic respiration by muscles produces more carbon dioxide, and therefore results in an increase in breathing depth and rate.
During intense physical activity, muscles may use anaerobic respiration as well as aerobic respiration, to supply extra energy. After exercise has finished, the lactic acid produced is broken down in the liver by aerobic respiration, which requires extra oxygen. This is called an oxygen debt.
Organisms need energy for muscle contraction, protein synthesis, cell division, active transport, growth, and maintaining a constant body temperature.
Organisms need energy for the passage of nerve impulses.
Respiration is a metabolic reaction that takes place in all living cells, and releases energy from glucose and other nutrient molecules.
Aerobic respiration happens in mitochondria. Oxygen is combined with glucose, releasing a lot of energy and producing carbon dioxide and water.
Anaerobic respiration happens in the cytoplasm. Glucose is broken down without using oxygen, releasing a small amount of energy. In humans, lactic acid is produced.
Lactic acid builds up in muscles and blood during vigorous exercise causing an oxygen debt. Oxygen debt is removed after exercise, by continuation of fast heart, deeper and faster breathing, and aerobic respiration of lactic acid in the liver.

PRACTICE QUESTIONS

1 **Identify** the approximate concentration of carbon dioxide in expired air.

A 0.16%
B 0.04%
C 4%
D 16% **[1]**

2 Identify the products of anaerobic respiration in human muscle cells.

A carbon dioxide only
B carbon dioxide and water
C lactic acid only
D lactic acid and water **[1]**

COMMAND WORD

identify: name/select/recognise.

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CONTINUED

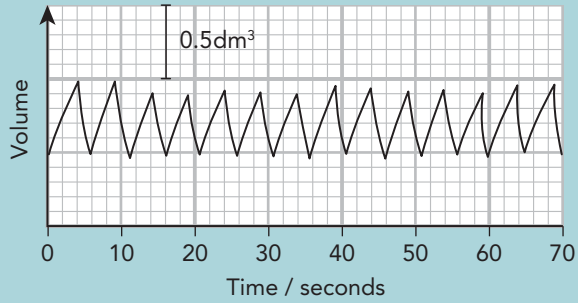
3 **a** **Give** the *word* equation for aerobic respiration. **[2]**

b Aerobic respiration releases energy that can be used by cells in the body.
State *three* ways in which the body uses this energy. **[3]**

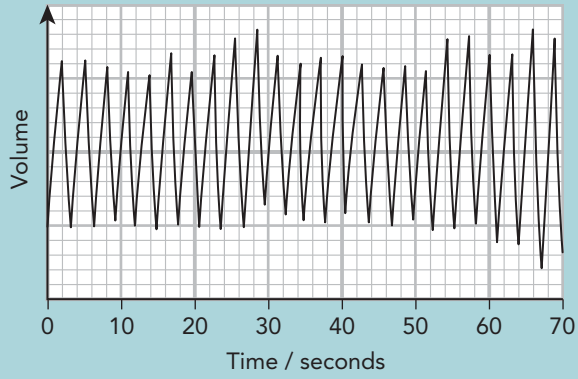
[Total: 5]

4 A girl breathed into apparatus that recorded the volume of air she breathed in and out. The results were recorded as a graph of volume against time. The graphs show the results obtained when she was resting and when she was exercising.

Results at rest



Results while exercising



a Use the first graph to **deduce**:
- **i** how many breaths per minute the girl took while she was resting **[1]**
- **ii** the volume of the first breath she took while she was resting. **[1]**

b Use the second graph to deduce:
- **i** how many breaths per minute she took while exercising **[1]**
- **ii** the volume of the second breath she took while exercising. **[1]**

c **Explain** how the brain was involved in the change in the girl's breathing when she exercised. **[4]**

d Explain how these changes in her breathing helped the girl to do the exercise. **[5]**

[Total: 13]

COMMAND WORDS

give: produce an answer from a given source or recall/memory.

state: express in clear terms.

COMMAND WORDS

deduce: conclude from available information.

explain: set out purposes or reasons/make the relationships between things clear/say why and/or how and support with relevant evidence.

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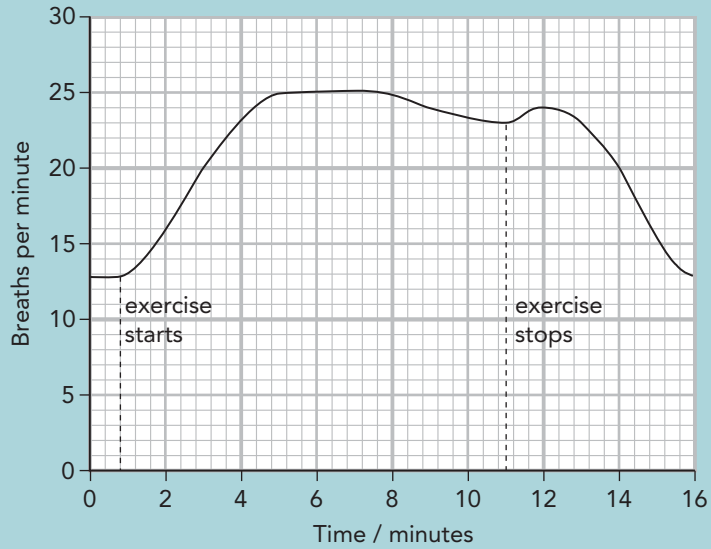
CONTINUED

5 The graph shows how a learner's breathing rate changed during and after exercise.



a **Calculate** how long it took, after he finished exercising, for his breathing rate to return to normal. **[1]**

b **Consider** why the learner's breathing rate did not return to normal immediately after exercise stopped. **[5]**

[Total: 6]

COMMAND WORDS

calculate: work out from given facts, figures or information.

consider: review and respond to given information.

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SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
describe the features of gas exchange surfaces in humans	B9.01			
identify the organs in the respiratory system in diagrams and images	B9.01			
investigate the differences in carbon dioxide content between inspired air and expired air, using limewater	B9.01			
explain the differences in composition between inspired air and expired air	B9.01			
investigate and describe the effect of physical activity on rate and depth of breathing	B9.01			
explain the effects of physical activity on rate and depth of breathing, including reference to lactic acid and oxygen debt, and the control of breathing rate by the brain	B9.01			
state the uses of energy in living organisms	B9.02			
describe aerobic respiration, and write the word equation for it	B9.02			
describe anaerobic respiration in human muscles, and write the word equation for it	B9.02			
write the balanced equations for aerobic respiration.	B9.02			

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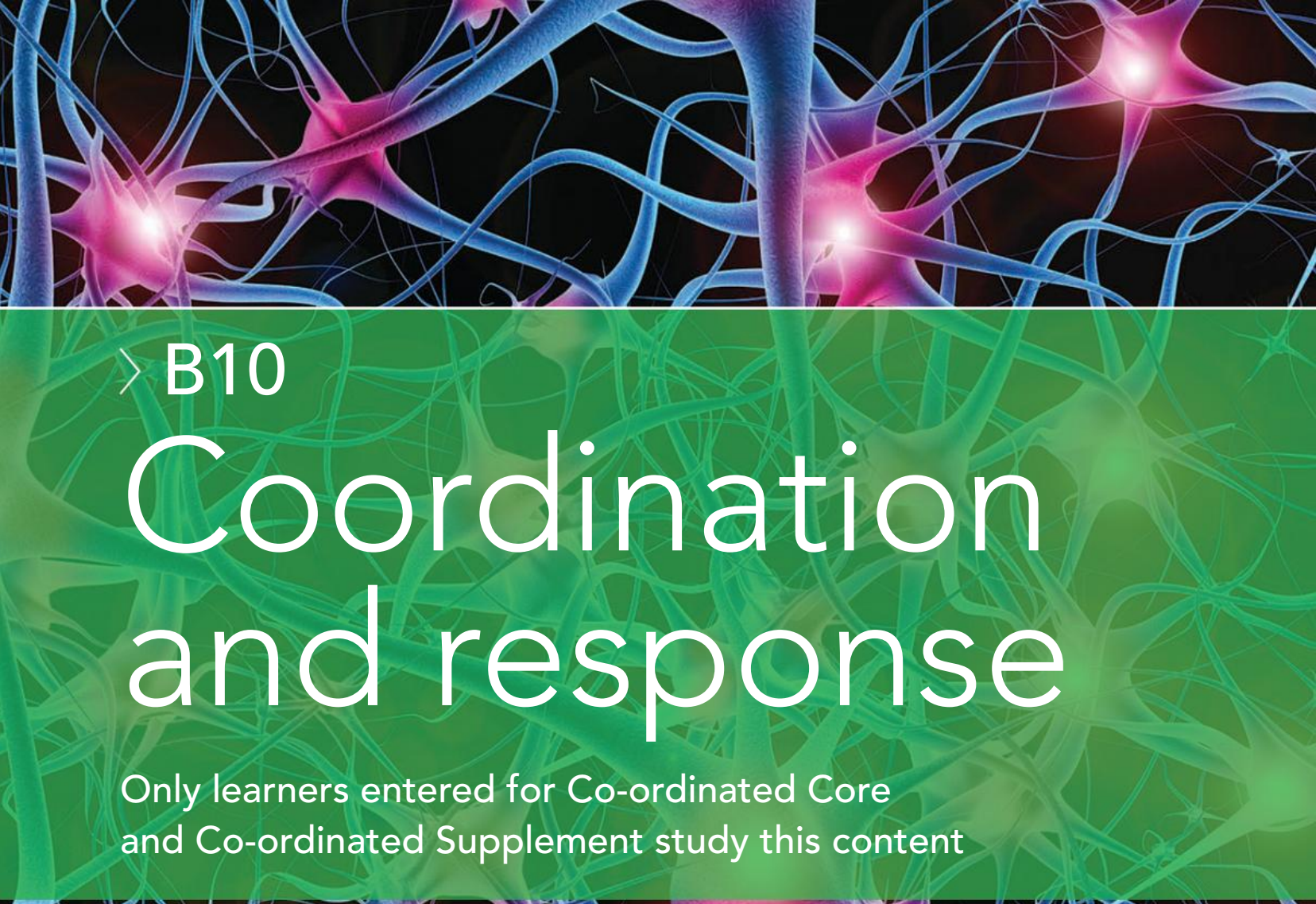
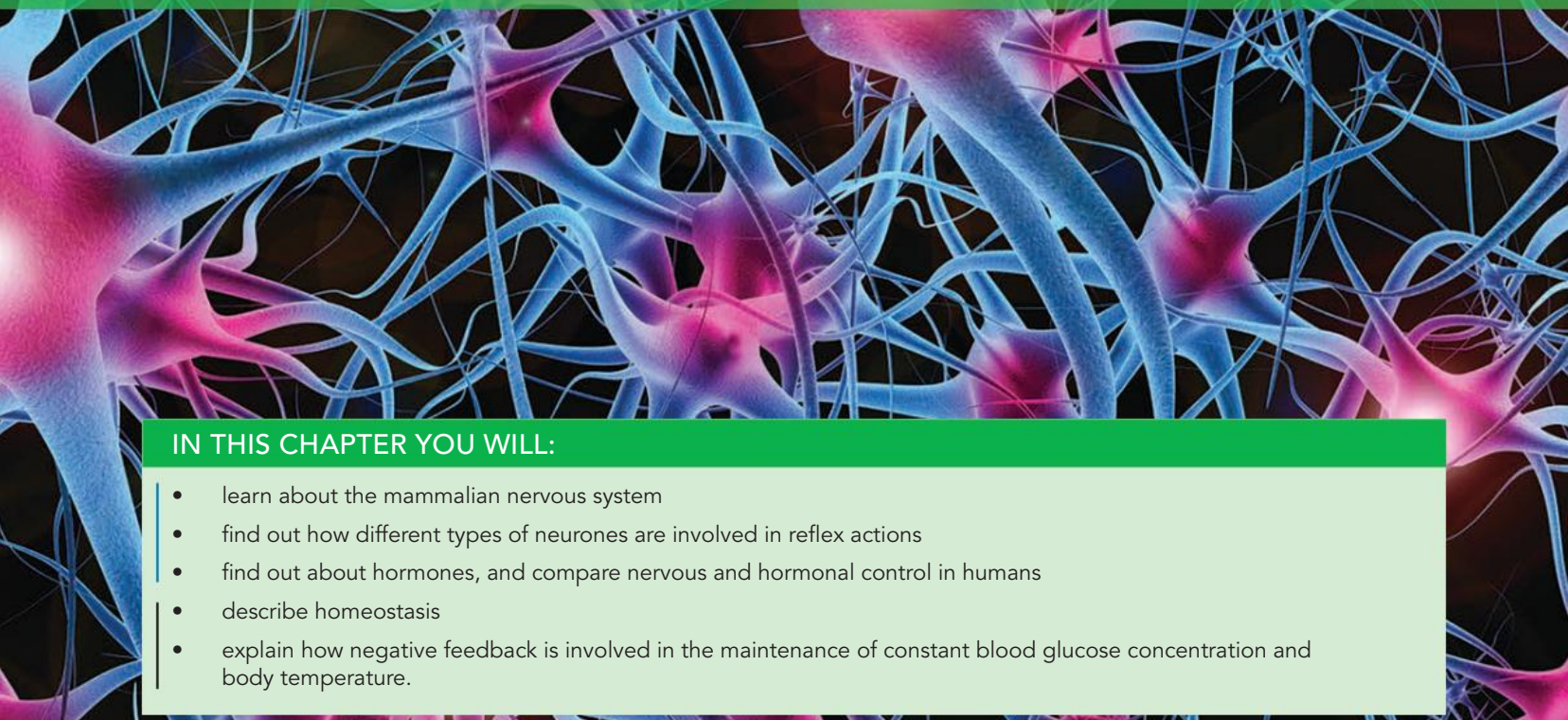


B10 Coordination and response

Only learners entered for Co-ordinated Core and Co-ordinated Supplement study this content



IN THIS CHAPTER YOU WILL:

- learn about the mammalian nervous system
- find out how different types of neurones are involved in reflex actions
- find out about hormones, and compare nervous and hormonal control in humans
- describe homeostasis
- explain how negative feedback is involved in the maintenance of constant blood glucose concentration and body temperature.

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BEFORE YOU START

- You probably remember that one of the characteristics of organisms is the ability to detect changes in the environment and respond to them.
- Sit quietly. Think about the different ways in which your body is detecting information about your environment.
- For example, what are your eyes detecting? When you close your eyes, what other features of the environment can you sense, and with which parts of your body?
- Share your ideas with the rest of the class and try to build a list of the different sense organs, and what they sense, in the human body.

SCIENCE IN CONTEXT B10.01

Reaction times

Having a fast reaction time is important in many sports, but in a short sprint event it could make the difference between a gold medal and a silver one.

Sprint races are started with a gun. Because sound takes time to travel, it is considered not to be fair for the starter to stand at one end of the starting line and simply fire the gun. The sound would take longer to reach the runner furthest away from the starter. Instead, the firing of the gun is silent, and is transmitted as an electrical signal along wires to individual speakers in each runner's starting block. Each runner should hear the sound of the gun at exactly the same moment.

In the men's 100 m race final in the 2016 Olympics in Rio de Janeiro, Usain Bolt's reaction time between hearing the gun and pushing off from his blocks was 0.155 s. Despite this relatively slow reaction time, Bolt won gold, completing the race in 9.81 s. The athletes who won silver and bronze medals – Justin Gatlin and Andre de Grasse – had reaction times of 0.152 s and 0.141 s, and completed the race in 9.89 and 9.91 s, respectively. However, these were not the fastest reaction times in that race; the fastest of all was that of Akani Simbine, which was only 0.108 s.

Most people's reaction times are longer than this, often around 0.2 s or more. Sprinters whose 'reaction time' is measured at less than 0.1 s are judged to have pushed off before the gun was fired, and they are disqualified.

In Figure B10.01, you can see the start of one of the semi-finals of the men's 100 m in Rio. The athlete in red was disqualified for a false start.

Figure B10.01: Sensors in the starting blocks measure the time between the gun being fired and each athlete's feet pushing back on the blocks.

Discussion question

1 How do you think the figure of 'less than 0.1 s reaction time', to determine a false start, was decided? Do you think this is fair?

B10.01 The nervous system

Changes in an organism's environment are called **stimuli (singular: stimulus)**. Stimuli are sensed by specialised cells called **receptors**. The organism responds using **effectors**. Muscles are effectors and may respond to a stimulus by contracting. Glands can also be effectors. For example, if you smell good food cooking, your salivary glands may respond by secreting saliva.

KEY WORDS

stimuli (singular: stimulus): changes in the environment that can be detected by organisms.

receptors: cells or groups of cells that detect stimuli.

effectors: parts of the body that respond to a stimulus; muscles and glands are effectors.

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Animals need fast and efficient communication systems between their receptors and effectors. This is partly because most animals need to be able to respond very quickly to catch their food or to avoid predators.

To make sure that the right effectors respond at the right time, there needs to be some kind of communication system between receptors and effectors. If you touch something hot, pain receptors on your fingertips send an electrical impulse to your arm muscles to make them contract, pulling your hand away from the hot surface. The way in which receptors detect stimuli, and then pass information on to effectors, is called **coordination**.

Most animals have two methods of sending information from receptors to effectors. The fastest is by means of **nerves**. The receptors and nerves make up the animal's nervous system. A slower method, but still a very important one, is by means of chemicals called hormones. Hormones are part of the endocrine system, and this is described in Topic B10.02 in this chapter.

KEY WORDS

coordination: ensuring that the actions of different parts of the body work together.

nerve: a group of neurone axons lying together (like an electrical cable containing many wires).

Neurones

The human nervous system is made of special cells called **neurones**. Figure B10.02 illustrates a particular type of neurone called a **motor neurone**.

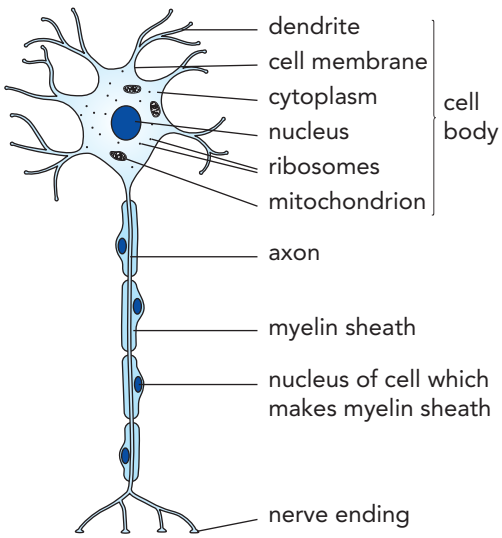

Figure B10.02: A motor neurone.

Neurones contain the same basic parts as any animal cell. Each has a nucleus, cytoplasm and a cell membrane. However, their structure is specially adapted to be able to carry electrical signals very quickly.

To enable them to do this, they have long, thin fibres of cytoplasm stretching out from the cell body. The longest fibre in a neurone is called an **axon** (see Figure B10.02). Axons can be more than a metre long. The shorter fibres are called **dendrites**.

The dendrites pick up electrical signals from other neurones lying nearby. These signals are called **nerve impulses**. The signal passes to the cell body, then along the axon, which might pass it to another neurone.

KEY WORDS

neurone: a cell that is specialised for conducting electrical impulses rapidly.

motor neurone: a neurone that transmits electrical impulses from the central nervous system to an effector.

axon: a long, thin, fibre of cytoplasm that extends from the cell body of a neurone.

dendrite: short fibre of cytoplasm in a neurone.

nerve impulse: an electrical signal that passes rapidly along an axon.

The human nervous system

All mammals (and many other animals) have a **central nervous system (CNS)** and a **peripheral nervous system (PNS)**. The CNS is made up of the brain and spinal cord (Figure B10.03). Like the rest of the nervous system, the CNS is made up of neurones. Its role is to coordinate the electrical impulses travelling through the nervous system.

KEY WORDS

central nervous system (CNS): the brain and spinal cord.

peripheral nervous system (PNS): the nerves outside the brain and spinal cord.

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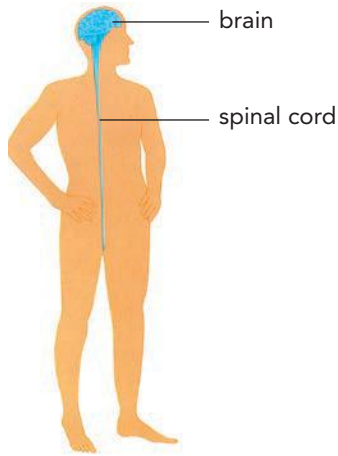

Figure B10.03: The human central nervous system.

The PNS is made up of nerves that spread out from the CNS. Each nerve contains hundreds of neurones. The PNS also includes the receptors in our sense organs.

When a receptor detects a stimulus, it sends an electrical impulse along a neurone to the brain or spinal cord. The brain or spinal cord receives the impulse, and sends it on, along the appropriate nerve fibres, to the appropriate effector.

Reflex arcs

Figures B10.04 and B10.05 show how these electrical impulses travel. If your hand touches a hot plate, a sensory receptor in your finger detects this. The receptor starts off an electrical impulse, which travels to the spinal cord along the axon from the receptor cell. This cell is called a **sensory neurone**, because it is carrying an impulse from a sensory receptor (Figures B10.04 and B10.05).

In the spinal cord, the neurone passes the electrical impulse to several other neurones. Only one is shown in Figure B10.04. These neurones are called **relay neurones**, because they relay the impulse on to other neurones. The relay neurones pass the impulse on to the brain. They also pass it on to a motor neurone to pass to an effector.

In this case, the effectors are the muscles in your arm. The electrical impulse travels to the muscle along the axon of a motor neurone. The muscle then contracts, so that your hand is pulled away.

The pathway along which the nerve impulse passes – the sensory neurone, relay neurones and motor neurone – is called a **reflex arc**.

KEY WORDS

sensory neurone: a neurone that transmits electrical impulses from a receptor to the central nervous system.

relay neurone: a neurone that transmits electrical impulses within the central nervous system.

reflex arc: a series of neurones (sensory, relay and motor) that transmit electrical impulses from a receptor to an effector.

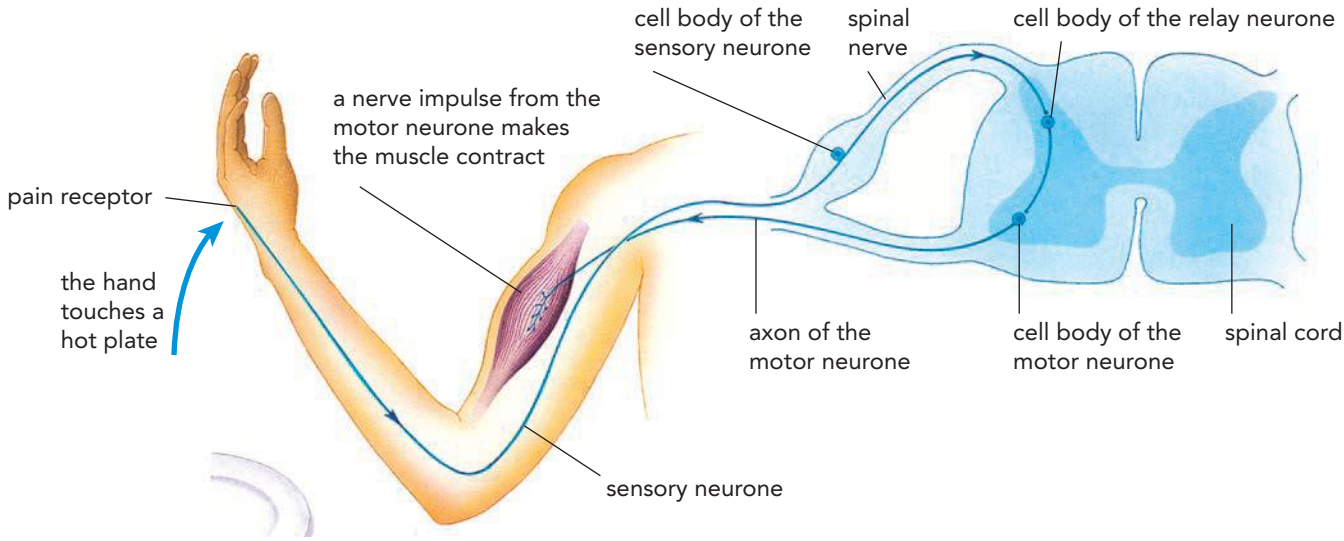

Figure B10.04: A reflex arc.

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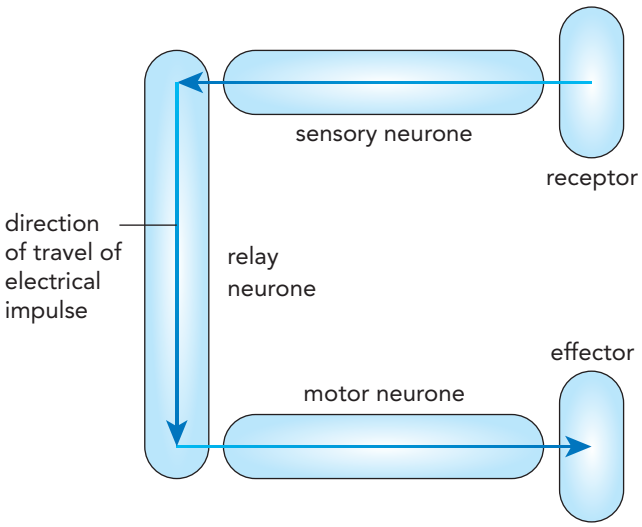

Figure B10.05: Schematic diagram of a reflex arc.

The three types of neurone that are involved in a reflex arc have different shapes. They are shown in Figure B10.06.

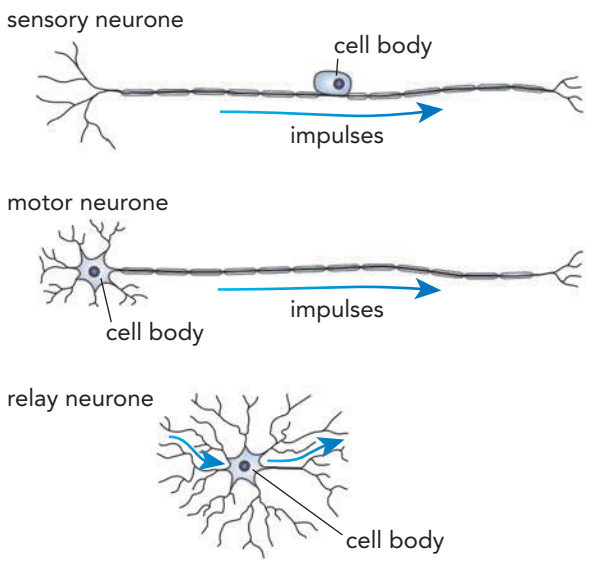

Figure B10.06: The structure of sensory, motor and relay neurones.

The reaction that happens after the impulse has sped around the reflex arc is called a **reflex action**. You do not need to think about reflex actions. Your brain is made aware of the action, but you only consciously realise what is happening after the electrical impulse has been sent on to your muscles.

KEY WORDS

reflex action: a means of automatically and rapidly integrating and coordinating stimuli with the responses of effectors.

Reflex actions are very useful because information gets from the receptor to the effector as quickly as possible. You do not waste time in thinking about what to do. Reflex actions are automatic actions. They help to coordinate our actions. If you receive more than one stimulus at once – such as the sound of a roar and the sight of a lion leaping towards you – these stimuli will be integrated (combined) to produce electrical impulses in sensory neurones. These impulses will travel very quickly around a reflex arc and produce an appropriate and very fast response.

Questions

B10.01 Describe *three* ways in which neurones are similar to other animal cells.

B10.02 Describe *one* way in which neurones are specialised to carry out their function of transmitting electrical impulses very quickly.

B10.03 Outline the function of the central nervous system.

B10.04 Look at Figure B10.04. Describe where the cell bodies of each of these types of neurone are found:

- **a** sensory neurone
- **b** relay neurone
- **c** motor neurone.

B10.05 Look at Figure B10.06. Describe, in words, the differences in structure between sensory neurones, relay neurones and motor neurones.

B10.06 Describe *two* reflex actions, other than pulling your hand away from a hot plate, or the knee jerk reflex. For each one, say what the stimulus is, where the receptor is and what the response is.

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ACTIVITY B10.01

Estimating the mean reaction time in your class

1. Get as many people as possible to stand in a big circle, holding hands.
2. One person lets go of his or her neighbour with their left hand and holds a stopwatch in it. When everyone is ready, this person simultaneously starts the stopwatch, and squeezes his or her neighbour's hand with their right hand.
3. As soon as each person's left hand is squeezed, he or she squeezes his or her neighbour with their right hand. The message of squeezes goes all round the circle.
4. While the message is going round, the person with the stopwatch puts it into their right hand and holds his or her neighbour's hand with the left hand. When the squeeze arrives, he or she should stop the watch.
5. Keep repeating this, until the squeeze is going round as fast as possible. Record the time taken, and also the number of people in the circle.
6. Now try again, but this time make the squeezes go the other way around the circle.

Questions

1. Using the fastest time you obtained, work out the mean time it took for one person to respond to the stimulus they received.
2. Did people respond faster as the experiment went on? Why might this happen?
3. Did the squeeze travel as quickly when you changed direction? Explain your answer.
4. Search the internet for a site that allows you to measure your reaction time. Try it out. Do you think the website gives you more reliable results than the 'circle' method? Compare the results you obtain and suggest the advantages and disadvantages of each method.

REFLECTION

The activity you tried with other members of your class is a good example of using an analogy. Analogies are useful models that provide an alternative way of thinking about something, so that it becomes easier to understand.

Can you think of any other analogies that you use in your studies?

Sense organs

The parts of an organism's body that detect stimuli, the receptors, may be specialised cells or just the endings of sensory neurones. In animals, the receptors are often part of a **sense organ** (Figure B10.07). A sense organ is a group of receptor cells that respond to a particular stimulus. Your eye, for example, is a sense organ, and contains receptor cells in the retina. These receptor cells are sensitive to light.

Figure B10.07: Which sense organs can you see in this photo?

KEY WORDS

sense organ: a group of receptor cells that are able to respond to a specific stimulus.

B10.02 Hormones

So far in this chapter, we have seen how nerves can carry electrical impulses very quickly from one part of an animal's body to another. Animals also use chemicals to transmit information from one part of the body to another.

The chemicals are called **hormones**. Hormones are made in special glands called **endocrine glands**. The hormones pass from the gland into the blood and are carried around the body in the blood plasma. Each hormone affects particular organs. These are called its **target organs**. The hormone alters the activity of these target organs.

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KEY WORDS

hormones: chemicals that are produced by a gland and carried in the blood, which alter the activities of their specific target organs.

endocrine glands: glands that secrete hormones.

target organs: organs whose activity is altered by a hormone.

Figure B10.08 shows the positions of some endocrine glands in the human body. Table B10.01 summarises their functions.

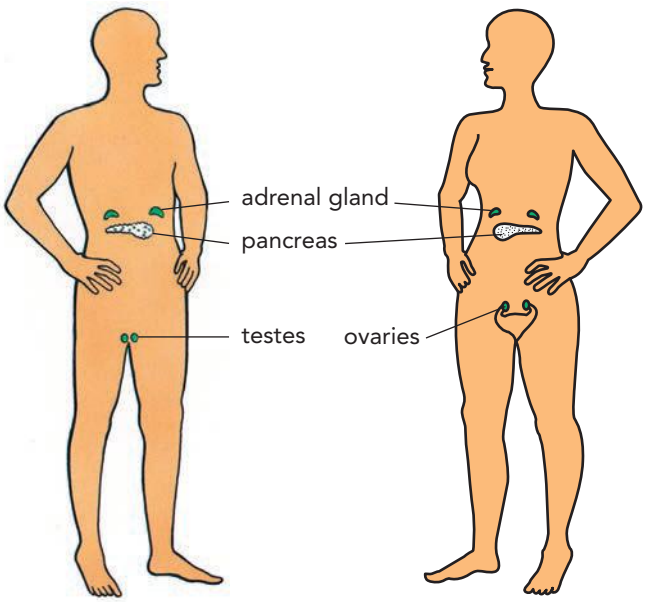

Figure B10.08: The positions of some endocrine glands in the body.

Adrenaline

There are two adrenal glands, one above each kidney. They make a hormone called **adrenaline**. When you are frightened or excited, your brain sends impulses along a nerve to your adrenal glands. This makes them secrete adrenaline into the blood.

Adrenaline has several effects which are designed to help you to cope with danger. These effects are known as the 'fight or flight' response. For example, your heart beats faster, supplying oxygen to your brain and muscles more quickly. This allows your muscles to carry out aerobic respiration more quickly, giving them more energy for fighting or running away. Your breathing rate increases, so that more oxygen can enter the blood in the lungs. Adrenaline also causes the pupils in the eye to widen. This allows more light into the eye, which might help you to see the danger more clearly.

Adrenaline causes the liver to release glucose into the blood. This extra glucose for the muscles, along with the extra oxygen provided by the increased breathing rate and heart rate, allows the muscles to increase their metabolic activity. You can read more about the control of blood glucose concentration later in this chapter.

KEY WORD

adrenaline: a hormone secreted by the adrenal glands, which prepares the body for fight or flight.

Gland	Hormone that it secretes	Function of hormone
adrenal gland	adrenaline	prepares body for vigorous action
pancreas	insulin	reduces the concentration of glucose in the blood
	glucagon	increases the concentration of glucose in the blood
testis (plural: testes)	testosterone	causes the development of male secondary sexual characteristics
ovary	oestrogen	causes the development of female secondary sexual characteristics, and helps in the control of the menstrual cycle

Table B10.01: Some important endocrine glands and their functions. Please note, glucagon and its function is Co-ordinated supplementary content in this table.

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Table B10.02 compares the nervous and endocrine systems.

Nervous system	Hormonal control system
made up of neurones	made up of glands
information transmitted in the form of electrical impulses	information transmitted in the form of chemicals called hormones
impulses transmitted along neurones	chemicals carried in the blood plasma
impulses travel very quickly, so action is fast	chemicals travel more slowly, so action is slower
effect of a nerve impulse usually only lasts for a very short time	effect of a hormone may last longer

Table B10.02: A comparison of the nervous and endocrine systems of a mammal.

Questions

B10.07 Name *three* endocrine glands, and the hormone that each secretes.

B10.08 Describe how hormones are transported around the body.

B10.09 Describe *two* situations in which adrenaline is likely to be secreted.

B10.10 Explain how adrenaline helps to prepare the body for action.

B10.03 Homeostasis

The environment (surroundings) of a living organism is always changing. Think about your own environment. The temperature of the air around you changes. For example, if you live in a temperate country, it might be −10 °C outside on a cold day in winter, and 23 °C indoors. If you live in the tropics, the outside temperature can be over 40 °C.

The cells inside your body, however, do not have a changing environment. Your body keeps the environment inside you almost the same, all the time. In the body, the temperature and the quantity of water in the blood are kept almost the same, all the time. So is the concentration of glucose in the blood. Keeping this **internal environment** constant is called **homeostasis**.

Homeostasis helps your cells to work as efficiently as possible. Keeping a constant temperature of around 37 °C helps enzymes to work at the optimum rate. Keeping a constant amount of water means that your cells are not damaged by absorbing or losing too much water by osmosis. Keeping a constant concentration of glucose means that there is always enough fuel for respiration.

In this topic, you will see how homeostasis occurs in humans. It involves the nervous system, as well as hormones.

Controlling blood glucose concentration

The control of the concentration of glucose in the blood is a very important part of homeostasis. Cells need a steady supply of glucose to allow them to respire. Without this, they cannot release the energy they need. Brain cells are especially dependent on glucose for respiration, and they die quite quickly if they are deprived of it.

On the other hand, too much glucose in the blood is not good either. It can cause water to move out of cells and into the blood by osmosis. This leaves the cells with too little water for them to carry out their normal metabolic processes.

Blood glucose concentration is controlled by hormones, secreted by the pancreas. If the blood glucose concentration gets too high – for example, after you have eaten a meal with a lot of sugar in it – the pancreas secretes a hormone called **insulin**. Insulin reduces the concentration of glucose in the blood.

The pancreas is two glands in one. Most of it is an ordinary gland with a duct. It makes pancreatic juice, which flows along the pancreatic duct into the duodenum (Chapter B6). Scattered through the pancreas, however, are groups of cells called islets (because they look like little 'islands' among a 'sea' of all the other cells).

KEY WORDS

internal environment: the conditions inside the body.

homeostasis: the maintenance of a constant internal environment.

insulin: a hormone secreted by the pancreas, which decreases blood glucose concentration.

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These cells do not make pancreatic juice. They make two hormones – insulin and **glucagon**. These hormones help the liver to control the amount of glucose in the blood. As we have seen, insulin has the effect of lowering blood glucose concentration. Glucagon does the opposite.

If you eat a meal that provides a lot of glucose, the concentration of glucose in the blood goes up. The islets in the pancreas detect this and secrete insulin into the blood (Figure B10.09). When insulin reaches the liver, it causes the liver to absorb glucose from the blood. Some is used for respiration, but some is converted into the insoluble polysaccharide, glycogen. This is stored in the liver.

If the blood glucose concentration falls too low, the pancreas secretes glucagon. This causes liver cells to break down glycogen to glucose and release it into the blood.

KEY WORD

glucagon: a hormone secreted by the pancreas, which increases blood glucose concentration.

Negative feedback and set points

In practice, our blood glucose concentration does not stay absolutely constant. A normal concentration is somewhere between 0.8 and 1.1 mg per cm^3 of blood. As we have around 5 dm^3 of blood in our body, this means we usually have a minimum of 4 g of glucose circulating in the bloodstream at any one time.

This range of normal values is called the **set point** for blood glucose concentration. The pancreas and liver work together to try to keep the values within this range.

KEY WORDS

set point: the normal value or range of values for a particular parameter – for example, the normal range of blood glucose concentration or the normal body temperature.

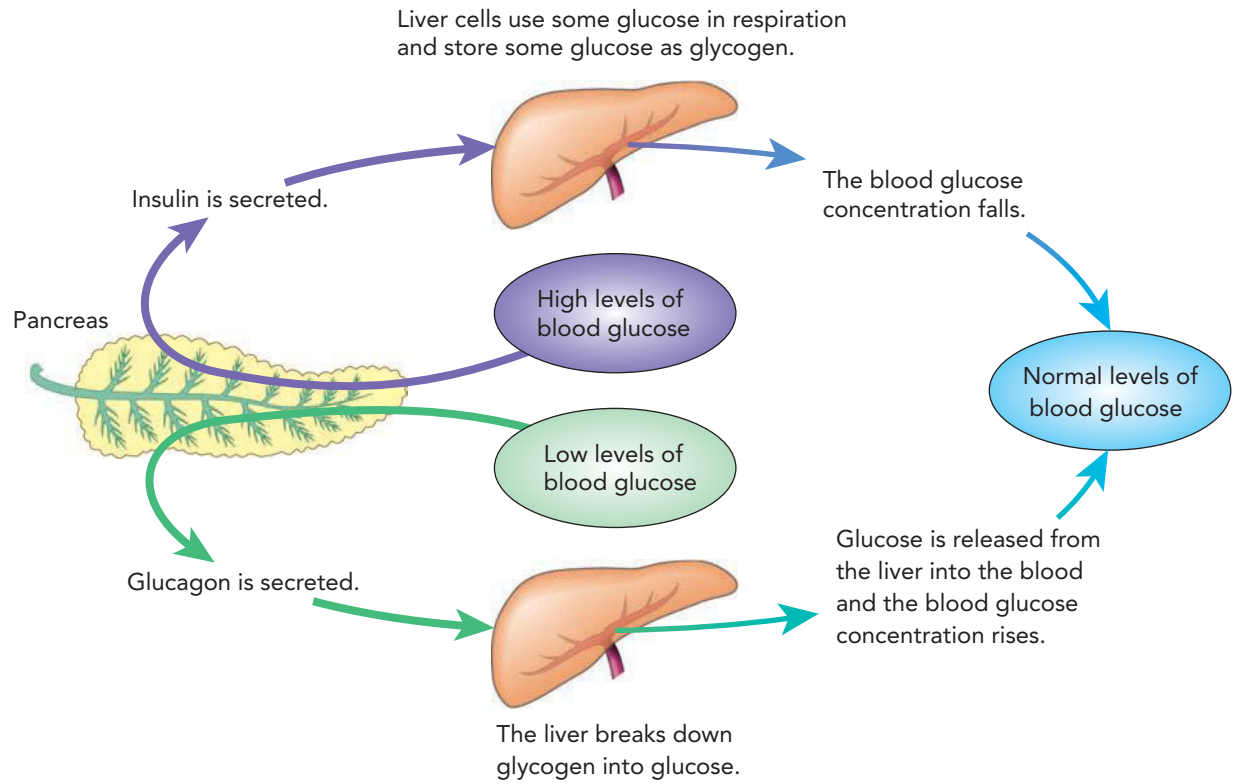

Figure B10.09: How blood glucose concentration is regulated. Start in the middle at either high or low levels of blood glucose and follow the arrows around.

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Various things can push the blood concentration above or below its set point. For example, you might eat a lot of sweets or ice cream, loading your blood with sugars that are absorbed from the ileum. Your blood glucose levels could rise well above the set point. Alternatively, you might forget to eat breakfast and then do some energetic sport in the morning. By lunchtime, your blood glucose concentration could have fallen below the set point.

In either case, cells in the pancreas detect that the blood glucose concentration is outside its normal limits. If it has risen too high, they secrete insulin. If it has fallen too low, they secrete glucagon.

The secretion of insulin causes the liver to absorb glucose from the blood, which reduces its concentration. The liver can use up some of this glucose in respiration, breaking it down to carbon dioxide and water. It can also change some of it to glycogen, linking many glucose molecules together into a long chain to make glycogen molecules. These can be stored in the liver cells.

The secretion of glucagon causes the liver to break down its glycogen stores. The glucose molecules that are produced move out of the liver and into the blood, increasing the blood glucose concentration so that it goes back towards normal.

This is an example of **negative feedback**.
In negative feedback:

- There is a set point. This is the normal level that the system tries to maintain.
- There is a 'measuring device' that keeps track of whether the level is within the range of the set point.
- If the level goes outside the set point, this triggers events to happen that bring the level back into line again.

These things do not happen instantaneously. For example, if your blood glucose concentration goes too high, it takes a short while for the cells in the pancreas to detect it. Then more time is needed for them to secrete insulin, for the insulin to get to the liver, and for the liver to take up glucose from the blood. Only then does the blood glucose concentration start to fall. This time lag means that the blood glucose concentration often goes up and down, around the set point, rather than staying absolutely steady.

KEY WORDS

negative feedback: a mechanism that detects a move away from the set point, and brings about actions that take the value back towards the set point.

Questions

B10.11 Explain how both insulin and glucagon fit the definition of a hormone.

B10.12 The graph in Figure B10.10 shows the blood glucose concentration in a healthy person. She ate a meal containing starch at time 0.

- **a** Describe the changes in the girl's blood glucose concentration between 0 and 5 hours.
- **b** Explain why the blood glucose concentration did not begin to rise until about 20 minutes after she ate her meal.
- **c** Explain what happened to make the blood glucose concentration fall.
- **d** Suggest why the blood glucose concentration fell below its starting value, before increasing again.

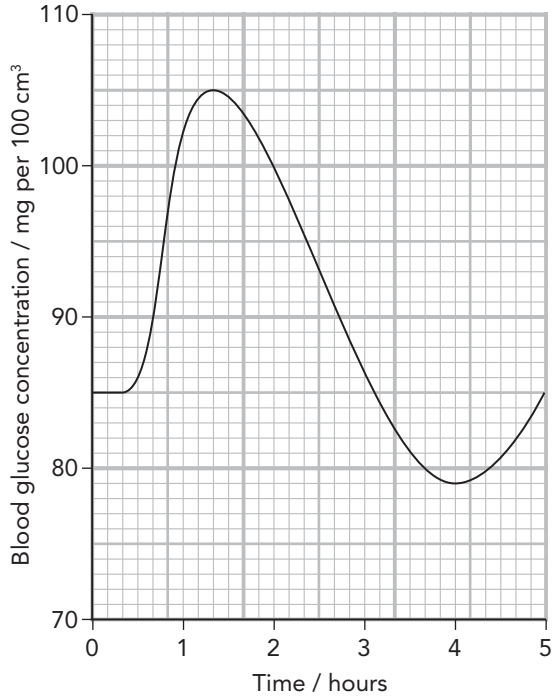

Figure B10.10: Blood glucose concentration in a healthy person.

B10.13 Insulin and glucagon are proteins. Explain why the cells in the islets of the pancreas contain many mitochondria and ribosomes.

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Controlling body temperature

Some animals – including ourselves – are very good at controlling their body temperature. They can keep their temperature almost constant, even though the temperature of their environment changes. This has great advantages. If the internal body temperature can be kept at around 37 °C, enzymes can always work very efficiently, no matter what the outside temperature is. **Metabolism** can keep going, even when it is cold outside. In cold weather or at night, the animal can be active when other animals are too cold to move.

The structure of human skin

One of the most important organs involved in temperature regulation in mammals is the skin. Figure B10.11 shows a section through human skin.

The skin is covered with a layer of dead cells, which form a tough, impermeable barrier that prevents water evaporating from the living cells below. It also prevents pathogens getting into the body.

Underneath this protective layer, many different types of living tissue are present. On the right-hand side of Figure B10.11, you can see a **sweat gland**. Sweat glands extract water and ions from the blood and produce the liquid that we call sweat. The sweat travels up the sweat duct to the skin surface and is released through a pore. As you will see, this plays an important part in temperature regulation.

You can see some blood vessels to the right of the sweat gland in the diagram. Arterioles bring oxygenated blood to the skin. These divide to form capillaries, which take blood up to just below the skin surface, before joining together again to form venules. You can also see shunt vessels that the blood can travel through without having to go all the way up to the skin surface.

Further to the left on the diagram, you will see a hair. Each hair has a tiny muscle attached to it, called a hair erector muscle. When this muscle contracts, it pulls the hair up straight.

On the left of the diagram, you can pick out two kinds of receptor. Some of these are sensitive to temperature. They send electrical impulses along sensory neurones if the temperature of the environment changes. Others are sensitive to pressure.

Underneath all of these structures is a layer of fat. This fatty tissue is made up of cells that contain large drops of oil. This layer helps to insulate your body against heat loss, and also acts as an energy reserve.

The hypothalamus

A part of the brain called the **hypothalamus** is at the centre of the control mechanism that keeps internal temperature

KEY WORDS

metabolism: chemical reactions that take place in living organisms.
sweat gland: a structure found in the skin of mammals, which secretes a watery fluid onto the skin surface to reduce body temperature.
hypothalamus: part of the brain that is involved in the control of body temperature.

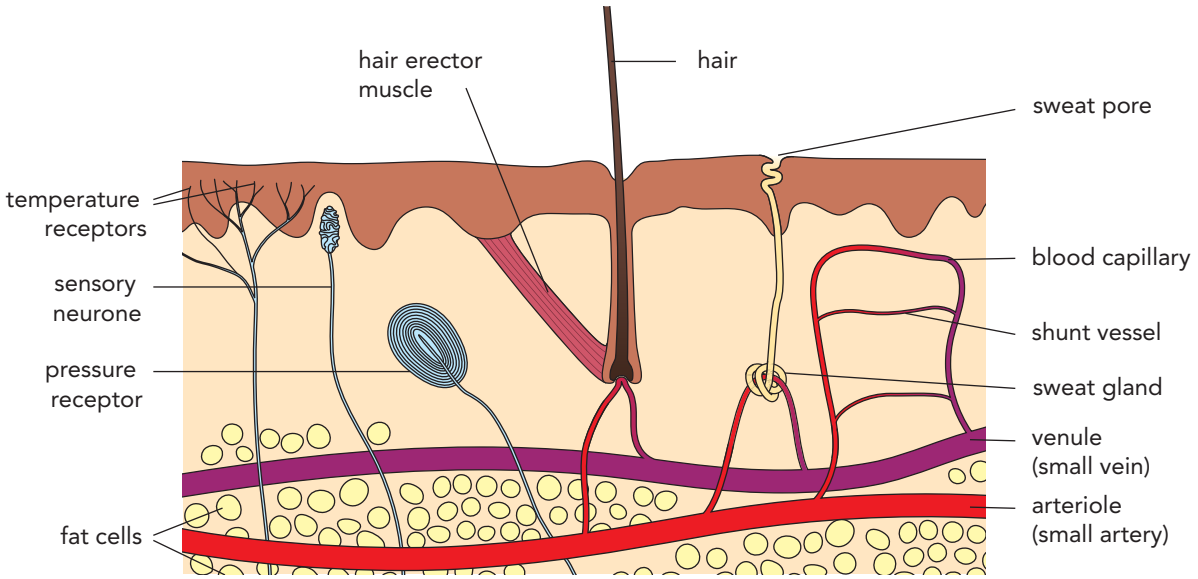

Figure B10.11: A section through human skin.

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constant. The hypothalamus coordinates the activities of the parts of the body that can help to keep the temperature of the blood at its set point.

The hypothalamus acts like a thermostat. It contains temperature receptors that sense the temperature of the blood running through it. If this is above or below 37 °C, then the hypothalamus sends electrical impulses, along neurones, to the parts of the body which have the function of regulating your body temperature.

Notice that we have two different sets of temperature receptors. There are the ones in the hypothalamus, which sense the temperature of the blood. There are also temperature receptors near the surface of the skin, which sense the temperature of the air or water around us. These can give us 'early warning' that the body temperature might be going to change. For example, if the receptors in the skin detect a very low temperature around us, this suggests that the body might be about to lose a lot of heat, making the body temperature fall. These receptors can send electrical impulses that help to prevent this happening, even before the temperature of the blood has changed.

When temperature changes

The set point for the internal body temperature of a human is about 37 °C. If the temperature of the blood flowing through the hypothalamus drops below 37 °C, the hypothalamus sends electrical impulses along motor neurones to the skin, muscles and liver. This causes the following things to happen (Figure B10.12).

When temperature falls

- Muscles contract: Muscles in some parts of the body contract and relax very quickly, in a process called shivering. They get the energy for this from respiration, and some of the energy is released as heat. The heat generated in the muscles warms the blood as it flows through them. The blood distributes this heat all over the body.
- Metabolism may increase: The speed of chemical reactions in other tissues, not only muscles, may increase. For example, the liver cells may respire faster. This also releases more heat.
- Hairs stand up: The erector muscles in the skin contract, pulling the hairs up on end. In humans, this does not do anything very useful – it just produces 'goose pimples'. But in a hairy animal, such as a cat, it traps a thicker layer of warm air next to the skin. This prevents the skin from losing more warmth. It acts as an insulator.
- Vasoconstriction: The arterioles that supply the blood capillaries near to the surface of the skin become narrower (constricted). This is called **vasoconstriction**. Only a very little blood can flow in the surface capillaries. The blood flows through the deep-lying capillaries instead. Because these are deep under the skin, beneath the insulating fatty tissue, the blood does not lose so much heat to the air.

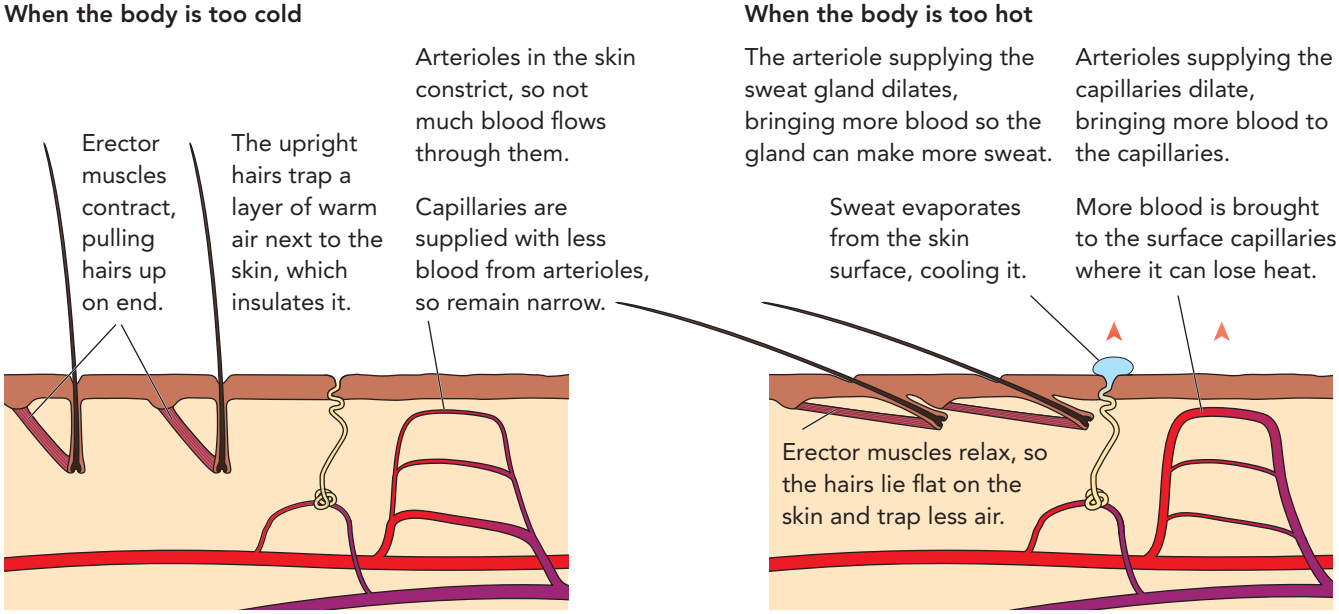

Figure B10.12: How skin helps with temperature regulation.

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- Sweat glands reduce secretion: Sweat glands reduce the quantity of sweat that they produce. As you will see, sweat helps to cool the body down, so it is not required when you want to warm up.

When temperature rises

When a rise in blood temperature is detected by the receptors in the hypothalamus, electrical impulses are sent along neurones to cause the following responses (Figure B10.12).

- Hairs lie flat: The erector muscles in the skin relax, so that the hairs lie flat on the skin. This allows heat to leave the skin through radiation into the air.
- **Vasodilation:** The arterioles supplying the capillaries near the surface of the skin become wider – they become dilated. This is called vasodilation. More blood, therefore, flows through these capillaries near the surface. Because a lot of blood is so near the surface of the skin, heat is readily lost from the blood into the air.
- Sweat production increases: The sweat glands secrete more sweat. The sweat lies on the surface of the hot skin. The water in it then evaporates, taking heat from the skin with it, thus cooling the body.

KEY WORDS

vasoconstriction: narrowing of arterioles, caused by the contraction of the muscle in their walls.

vasodilation: widening of arterioles, caused by the relaxation of the muscle in their walls.

ACTIVITY B10.02

Comparing the control of temperature regulation with blood glucose concentration

Work in a group of three for this activity.

Look again at the descriptions of negative feedback and the control of blood glucose concentration. Think about similarities between that process, and the way that body temperature is controlled.

For example:

- They both have receptors that detect changes. Where are these, and what do they detect?
- They both involve set points. What is this for each of them?
- They both involve negative feedback. How does this happen, in each of them?

Now try constructing a diagram, similar to the one in Figure B10.12, to summarise and illustrate the control of body temperature.

Peer assessment

Exchange your diagram with another group.

How well do you think they have succeeded? Does the diagram 'work' – that is, if you follow the arrows around, does the sequence of events make sense?

How can you improve your own group's diagram?

PROJECT B10.01 TEACHING ABOUT HOW NEGATIVE FEEDBACK WORKS

Negative feedback can be a tricky topic to understand. In this project, you will work in a small group to plan and present a short lesson to help people understand how negative feedback works in homeostasis.

Your lesson should:

- last no more than 8 to 10 minutes
- include some active learning for your pupils, where they have to do something and think for themselves, rather than just listening to you
- concentrate on one example of negative feedback in homeostasis
- not try to do too much – your lesson should not be a full-length lesson done at top speed, but just a small part of a lesson done properly.

Your lesson could also:

- use other examples of negative feedback to help people to understand – for example, how a thermostat works in a heating or cooling system in a house
- use a slide show or video clip that you have constructed yourself
- use other IT if you have it, such as tablets (Figure B10.13).

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CONTINUED

First, work as a group to plan your lesson.
Think about these issues:

1. How do you plan to explain negative feedback? How can you make this easy for people to understand?
2. How will you start your lesson? How will you get everyone's attention right at the beginning?
3. What resources do you need? You might want to use drawings, handouts, slides or video clips, for example.
4. How will you check that your class understands your explanation? What questions will you ask, to find out how well they understand?

When every group has planned their lesson, each group should give their lesson to the rest of the class.

Be ready to give feedback to each group.
How interesting and helpful was their lesson?
What has the group done well? What could they do better?

Figure B10.13: Using tablets in the classroom.

SUMMARY

In mammals, the nervous system is made up of the central nervous system and the peripheral nervous system. The nervous system coordinates and helps to regulate body functions.
Neurones transmit information in the form of electrical impulses.
A reflex arc consists of a sensory neurone, relay neurone and motor neurone. An impulse produced in a receptor passes along the sensory neurone, into the relay neurone, then the motor neurone, and then to an effector. The effector takes action, bringing about a reflex action. Reflex actions are fast and automatic.
Hormones are chemicals that are secreted by glands and travel in the blood. They alter the activity of target organs.
The adrenal glands secrete adrenaline, which prepares the body for fight or flight by increasing breathing rate, heart rate and the diameter of the pupil.
Adrenaline increases metabolic activity, increasing blood glucose concentration and the supply of glucose and oxygen to body organs, by increasing heart rate and breathing rate.
Homeostasis is the maintenance of a constant internal environment.
Insulin is secreted by the pancreas when blood glucose concentration is too high. It decreases blood glucose concentration.
In homeostasis, negative feedback helps to keep a value close to its set point.
Blood glucose concentration is controlled by a negative feedback loop involving the pancreas and liver.
When blood glucose concentration rises above its set point, insulin is secreted by the pancreas. This causes the liver to take up glucose from the blood, and to use some in respiration and also convert some to glycogen and store it.

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CONTINUED

When blood glucose concentration falls below its set point, glucagon is secreted by the pancreas. This causes the liver to break down some of its glycogen stores, and release glucose into the blood.
Temperature is controlled by a negative feedback loop involving receptors in the skin and hypothalamus in the brain, and effectors in the skin and muscles.
When body temperature rises above its set point, the hypothalamus sends electrical impulses along motor neurones to the skin. This causes arterioles supplying the skin surface capillaries to dilate, in a process called vasodilation. More blood flows close to the surface and more heat is lost to the air. Also, the sweat glands secrete more sweat, which evaporates from the skin surface, producing a cooling effect.
When body temperature falls below its set point, the hypothalamus sends electrical impulses along motor neurones to the skin. This causes arterioles supplying the skin surface capillaries to get narrower, in a process called vasoconstriction. Blood is diverted to capillaries deeper in the skin, so that less heat is lost to the air.
Fatty tissue underneath the skin helps to insulate the body, reducing heat loss to the air.

PRACTICE QUESTIONS

1 **Identify** the parts of the peripheral nervous system.

A the brain and spinal cord

B the brain and nerves

C the nerves outside the brain and spinal cord

D the spinal cord only **[1]**

2 In negative feedback, a receptor detects when a value has moved outside a set point. Identify the location of the receptor that detects when blood glucose concentration is outside its set point.

A in the brain

B in the kidneys

C in the liver

D in the pancreas **[1]**

3 **a** Adrenaline and insulin are examples of hormones.

i **Define** *hormone*. **[3]**

ii **Give** the name of the gland that secretes adrenaline. **[1]**

iii Give the name of the gland that secretes insulin. **[1]**

b **Outline** *two* ways in which control by hormones such as adrenaline and insulin differs from control by nerves. **[2]**

[Total: 7]

COMMAND WORDS

identify: name/select/recognise.

define: give a precise meaning.

give: produce an answer from a given source or recall/memory.

outline: set out main points.

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CONTINUED

4 **a** A boy ate some rice, which contains starch.

i **Describe** how and where the starch is broken down to glucose in his body. **[3]**

ii Give the name of the part of the digestive system where the glucose is absorbed into the blood. **[1]**

b Use your knowledge of osmosis to **explain** how a high concentration of glucose in the blood could harm body cells. **[2]**

c Shortly after the boy ate the rice, the quantity of insulin in his blood increased.

i Give the name of the gland that secretes insulin. **[1]**

ii **State** the effect of insulin on blood glucose concentration. **[1]**

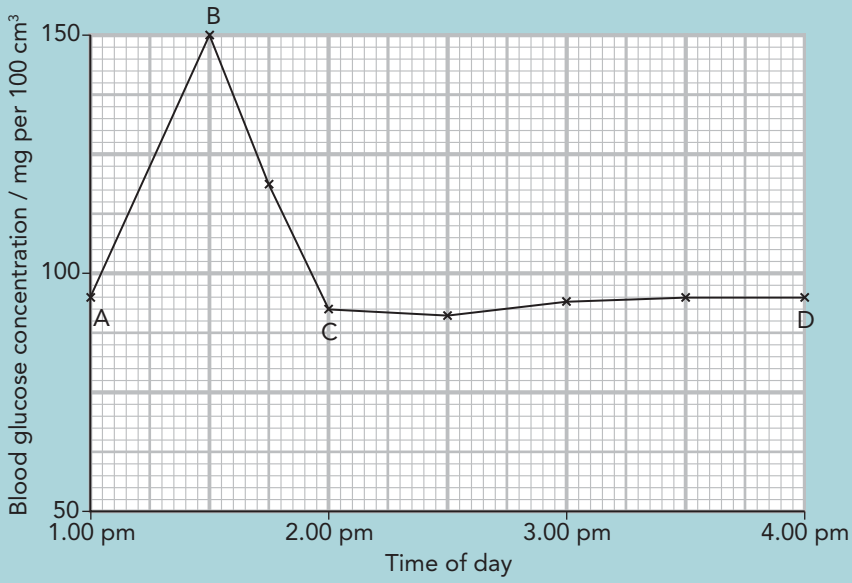
[Total: 8]

5 **a** Explain why body cells need a constant supply of glucose. **[3]**

b In healthy humans, the blood normally contains about 100 mg of glucose per 100 cm^3 of blood.

Give the name of the gland that secretes the hormones that help to keep this concentration fairly constant. **[1]**

c The graph shows the changes in concentration of blood glucose after a meal containing starch.



i Explain why the concentration of glucose in the blood rises between A and B. **[3]**

ii Explain why the concentration of glucose in the blood falls between B and C. **[4]**

d The graph shows that the blood glucose concentration remains fairly constant between C and D. Explain the role of negative feedback in keeping blood glucose concentration constant. **[3]**

COMMAND WORDS

describe: state the points of a topic/give characteristics and main features.

explain: set out purposes or reasons/ make the relationship between things evident/ provide why and/or how and support with relevant evidence.

state: express in clear terms.

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CONTINUED

e In people with type 1 diabetes, the pancreas cannot produce insulin. **Sketch** a curve on a copy of the graph to show how you would expect the blood glucose concentration of a person with type 1 diabetes to change, if they ate the same meal at the same time. **[3]**

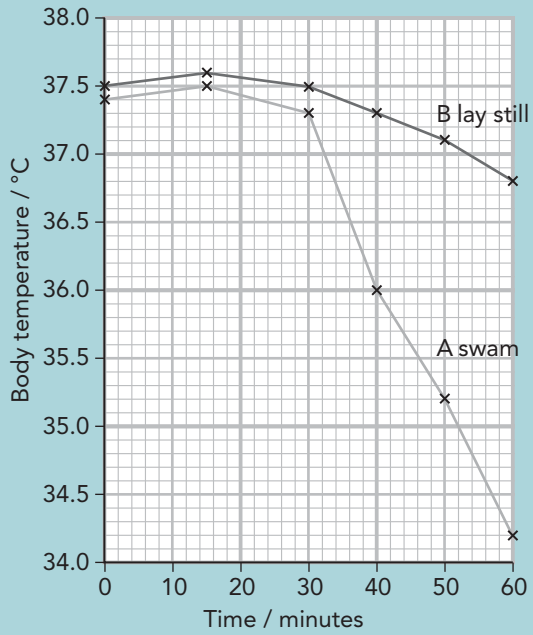
[Total: 17]

6 When a person is submerged in cold water, their body temperature can drop very quickly. This is because heat is transferred quickly, by conduction, from the warm body into the cold water.

An experiment was carried out to see if it is better to stay still if you fall into cold water or to try to swim.

- Two men sat for 30 minutes, in air at a temperature of 15 °C.
- They then got into a swimming pool, where the water was also at a temperature of 15 °C.
- Person A swam for the next 30 minutes. Person B lay still in the water.

The body temperatures of both men were measured at 10-minute intervals throughout the experiment. The results are shown below.



a State the body temperatures of both men at the start of the experiment. **[2]**

b Explain why their body temperatures remained roughly constant for the first 30 minutes of the experiment. **[4]**

c Explain why the body temperatures of both men dropped between 30 minutes and 60 minutes. **[2]**

d **Suggest** why person A's temperature dropped faster than person B's temperature during this time period. **[3]**

[Total: 11]

COMMAND WORD

sketch: make a simple freehand drawing showing the key features, taking care over proportions.

COMMAND WORD

suggest: apply knowledge and understanding to situations where there is a range of valid responses in order to make proposals/put forward considerations.

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SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
state that electrical impulses travel along neurones	B10.01			
state what the central nervous system and the peripheral nervous system consist of and what they do	B10.01			
describe a simple reflex arc, including the positions and roles of sensory, relay and motor neurones; and explain how this arc transmits an impulse from a receptor to an effector	B10.01			
describe a reflex action as a means of automatically and rapidly integrating and coordinating stimuli and responses	B10.01			
explain what a hormone is and list the hormones produced by the adrenal glands, pancreas, testes and ovaries	B10.02			
describe how adrenaline prepares the body for fight or flight	B10.02			
define homeostasis	B10.03			
describe the effect of insulin	B10.03			
explain how negative feedback keeps values close to a set point	B10.03			
describe how the liver and the pancreas (which secretes insulin and glucagon) keep blood glucose concentration close to a set point	B10.03			
identify structures on a diagram of the skin	B10.03			
describe how the hypothalamus in the brain helps in temperature regulation	B10.03			
describe how insulation, sweating, shivering, vasodilation and vasoconstriction help to keep body temperature close to a set point.	B10.03			

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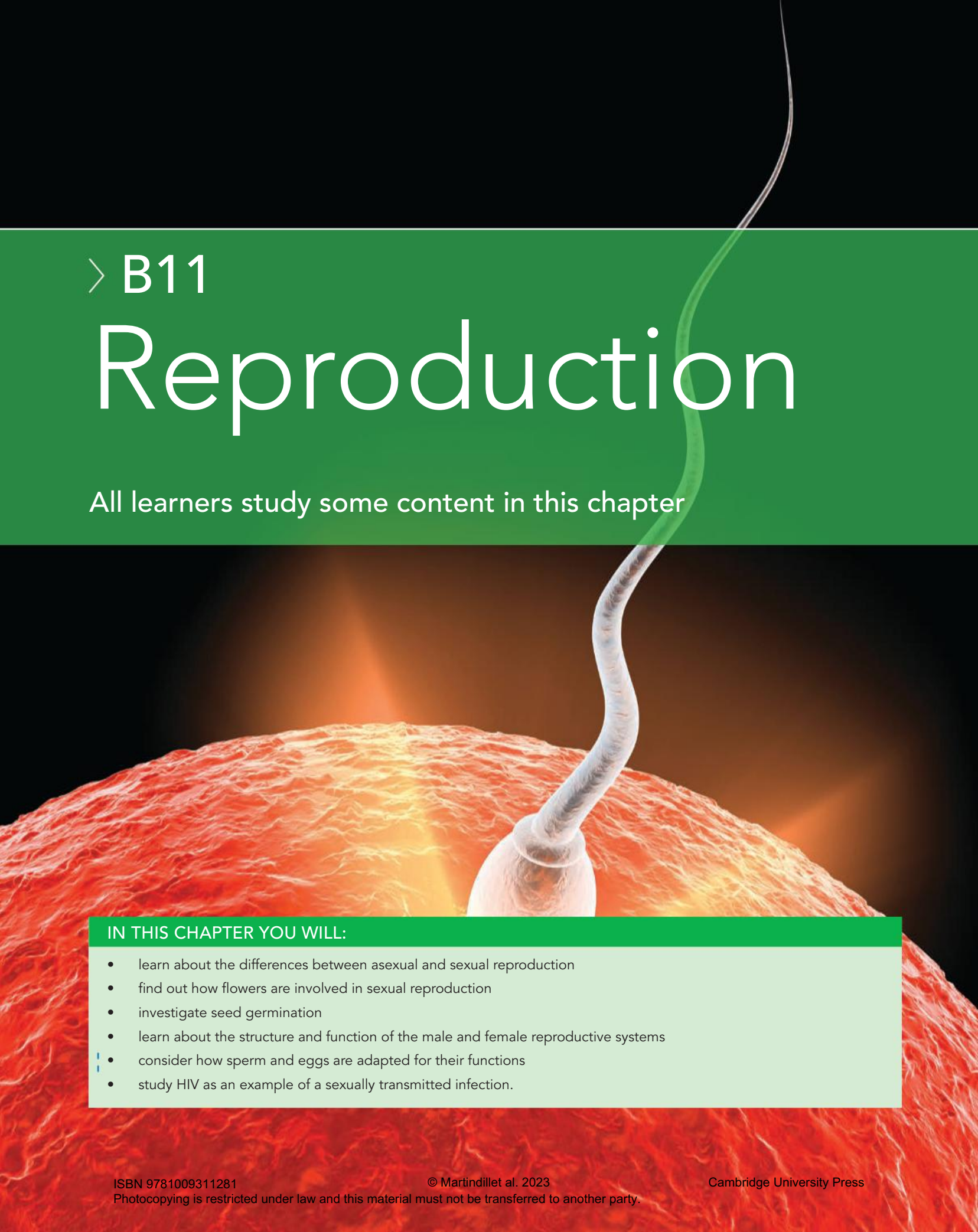
B11

Reproduction

All learners study some content in this chapter



IN THIS CHAPTER YOU WILL:

- learn about the differences between asexual and sexual reproduction
- find out how flowers are involved in sexual reproduction
- investigate seed germination
- learn about the structure and function of the male and female reproductive systems
- consider how sperm and eggs are adapted for their functions
- study HIV as an example of a sexually transmitted infection.

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BEFORE YOU START

Look at the photographs in Figure B11.01. They both show a strawberry plant reproducing.
With a partner, discuss what is happening in each plant. How is each one reproducing?

Figure B11.01: Two methods of reproduction in strawberry plants.

SCIENCE IN CONTEXT B11.01

Homunculus theory

In 1654, a Dutch scientist, Anton van Leeuwenhoek, looked down his microscope at a sample of semen. He was the first person to see sperm, and he made careful drawings of them (Figure B11.02). However, he was too embarrassed to talk about his findings until a student, Johan Ham, spoke to him in 1677, about what he himself had seen when studying semen under the microscope. He said that he could see small animals with tails.

Leeuwenhoek gradually overcame his reluctance to talk about his findings and shared them with other scientists. As more and more people continued these studies, various theories emerged about how human life began. One suggestion was that these 'small animals with tails' each contained a tiny human being – a homunculus. Indeed, in 1695 Nicholas Hartsoecker, a Dutch physicist, made a drawing of what he thought one might look like, though he made it clear that he never actually saw one through his microscope (Figure B11.03).

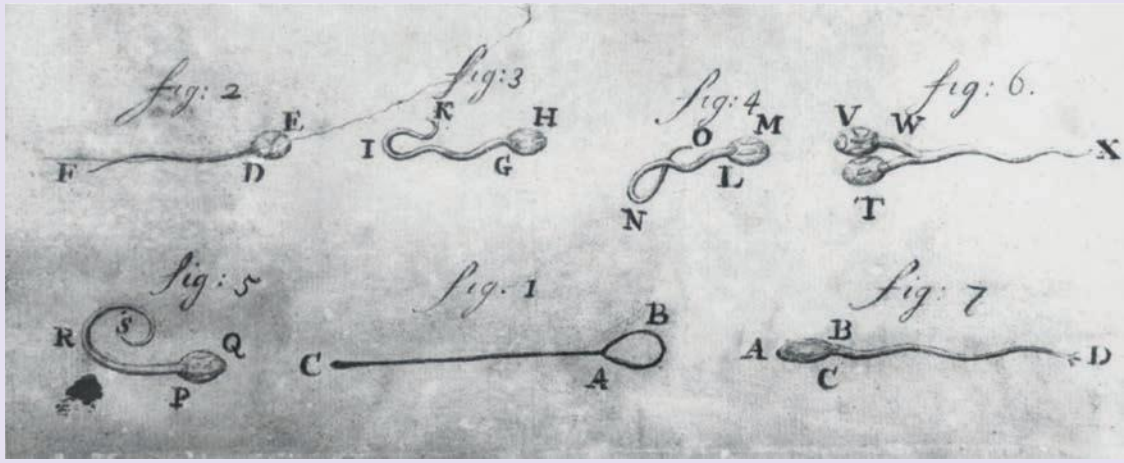

Figure B11.02: Leeuwenhoek's drawings of sperm.

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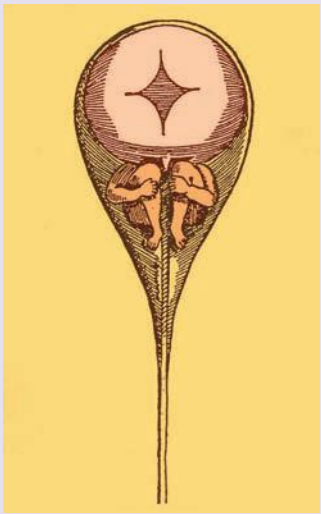

Figure B11.03: Nicholas Hartsoecker's drawing of a homunculus.

At this time, no one understood that an egg was also involved in creating a new life. This caused difficulties in explaining why children resembled both their father and their mother. One idea was the little developing homunculus gradually absorbed characteristics of its mother as it developed inside her uterus.

Discussion question

1 Nicholas Hartsoecker had no evidence for his drawing of a homunculus, yet many people believed his ideas. Even in the 21st century, ideas for which there is no evidence spread widely. Why do you think so many people believe these ideas?

B11.01 Asexual and sexual reproduction

Reproduction is one of the characteristics of all living things.

Each kind of organism has its own particular method of reproducing, but all of these methods fit into one of two categories: **asexual reproduction** or **sexual reproduction**.

In reproduction, each new organism obtains a set of chromosomes from its parent or parents. Chromosomes are long threads of DNA found in the nucleus of a cell. They contain sets of instructions known as genes. As you will find out in Chapter B12, these genes vary slightly from one another in different individuals.

KEY WORDS

asexual reproduction: a process resulting in the production of genetically identical offspring from one parent.

sexual reproduction: a process involving the fusion of the nuclei of two gametes to form a zygote and the production of offspring that are genetically different from each other.

Asexual reproduction

Asexual reproduction involves just one parent. Some of the parent's cells divide to produce new cells that contain exactly the same genes as the parent cell. They are said to be genetically identical. They grow into new organisms, which are all genetically identical to each other and to their single parent.

An example of asexual reproduction

Many plants are able to reproduce asexually, and gardeners and farmers make use of this. Asexual reproduction can quickly and efficiently produce many new plants, all genetically identical to one another. This is advantageous to the grower if the original plant has exactly the characteristics that are wanted, such as large and attractive flowers, or good flavour, or high yield.

Potatoes, for example, reproduce using stem tubers (Figure B11.04). When it is warm enough, some of the plant's stems grow normally and produce leaves above ground, which photosynthesise. Other stems grow under the soil. Swellings called tubers form on them. Sucrose is transported from the leaves into these underground stem tubers, where it is converted into starch and stored. The tubers grow larger and larger. Each plant can produce many stem tubers.

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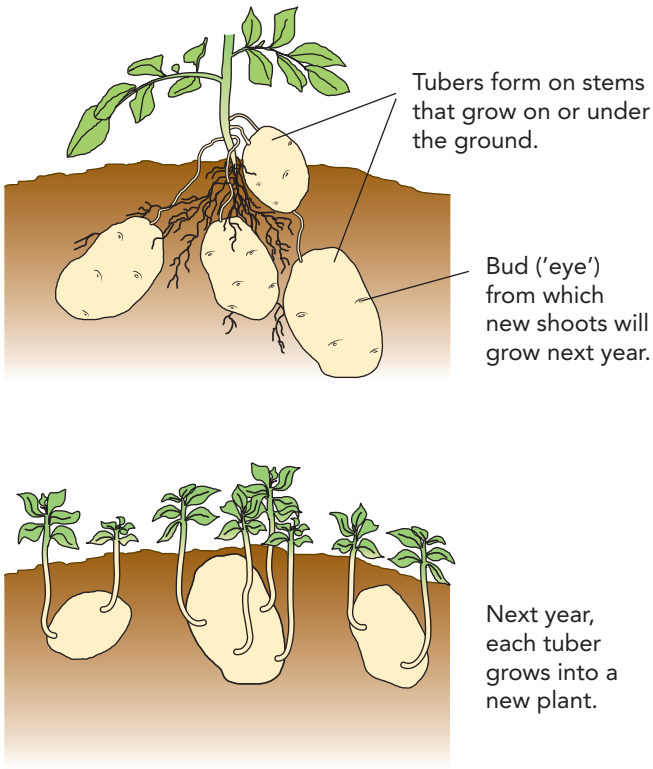

Figure B11.04: Asexual reproduction in potatoes.

The tubers are harvested, to be used as food. Some of them, however, are saved to produce next year's crop. These tubers are planted underground, where they grow shoots and roots to form a new plant. Because each potato plant produces many tubers, one plant can give rise to many new ones. To get even more plants, each tuber can be cut into several pieces. As long as each piece has a bud on it, it can grow into a complete new plant.

Plants are not the only organisms that can reproduce asexually. Bacteria, for example, reproduce asexually when one cell splits into two cells. Even some simple animals can reproduce asexually. A tiny animal called *Hydra*, which lives in fresh water and is related to sea anemones, reproduces asexually by growing 'buds'. These 'buds' develop into young *Hydra* before breaking away from the parent (Figure B11.05).

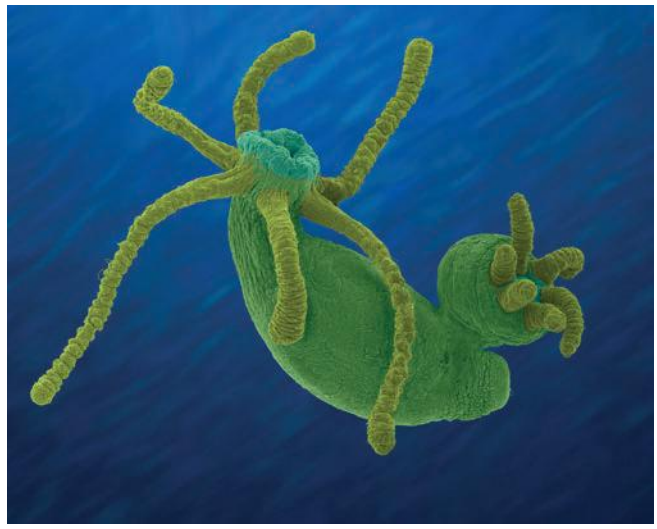

Figure B11.05: The bud on this *Hydra* is almost ready to break away and start an independent life.

Sexual reproduction

A **species** is a group of organisms that can sexually reproduce with each other to produce offspring that can also reproduce. The offspring are **fertile**. (Species is an unusual word, because the singular and plural are exactly the same – one species and many species.)

For example, horses belong to the species *Equus caballus*. Members of this species can reproduce with each other. The offspring are also horses. They belong to the same species, and they can reproduce again to produce more horses.

Donkeys belong to a different species, *Equus asinus*. Donkeys reproduce with each other to produce fertile donkeys. But donkeys can also reproduce with horses. If a male donkey reproduces with a female horse, the offspring is a mule. They are usually strong, healthy organisms, but they cannot reproduce. They are **infertile**.

KEY WORDS

species: a group of organisms that can reproduce to produce fertile offspring.

fertile: able to reproduce.

infertile: not able to reproduce.

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In sexual reproduction, the parent organism produces sex cells called **gametes**. Eggs and sperm are examples of gametes. Two of these gametes join and their nuclei fuse together. This is called **fertilisation**. The new cell which is formed by fertilisation is called a **zygote**. The zygote divides again and again, and eventually grows into a new organism.

The zygote contains chromosomes from both its parents. It can have any combination of their genes. Sexual reproduction, therefore, produces offspring that are genetically different from each other and from their parents.

KEY WORDS

gamete: a sex cell; a cell with half the normal number of chromosomes, whose nucleus fuses with the nucleus of another gamete during sexual reproduction.

fertilisation: the fusion of the nuclei of two gametes.

zygote: a cell that is formed by the fusion of two gametes.

Gametes

Gametes are different from ordinary cells, because they contain only half as many chromosomes as usual. This is so that when two of them fuse together, the zygote they form will have the correct number of chromosomes (Figure B11.06).

In most organisms that reproduce sexually, there are two types of gamete. Female gametes tend to be relatively large, and they do not move. In plants, the female gamete is a nucleus inside an ovule. In animals, it is called an egg. Male gametes are usually much smaller, and they can move. In plants, the male gamete is found inside the pollen grains. In animals, the male gametes are called sperm.

In humans, there are two sets of chromosomes in each cell. One of these sets came from the father, and one from the mother. Each set contains 23 chromosomes, so in total there are 46 chromosomes in each body cell. A cell or a nucleus that has two complete sets of chromosomes is said to be **diploid**.

But human egg and sperm cells only have 23 chromosomes each. They each have a single set of chromosomes. A cell or a nucleus containing a single set of chromosomes is said to be **haploid**. Gametes are haploid.

When an egg and sperm fuse together at fertilisation, the zygote which is formed will therefore have 46 chromosomes, the normal number. Zygotes are diploid.

KEY WORDS

diploid: having two complete sets of chromosomes.

haploid: having only a single set of chromosomes.

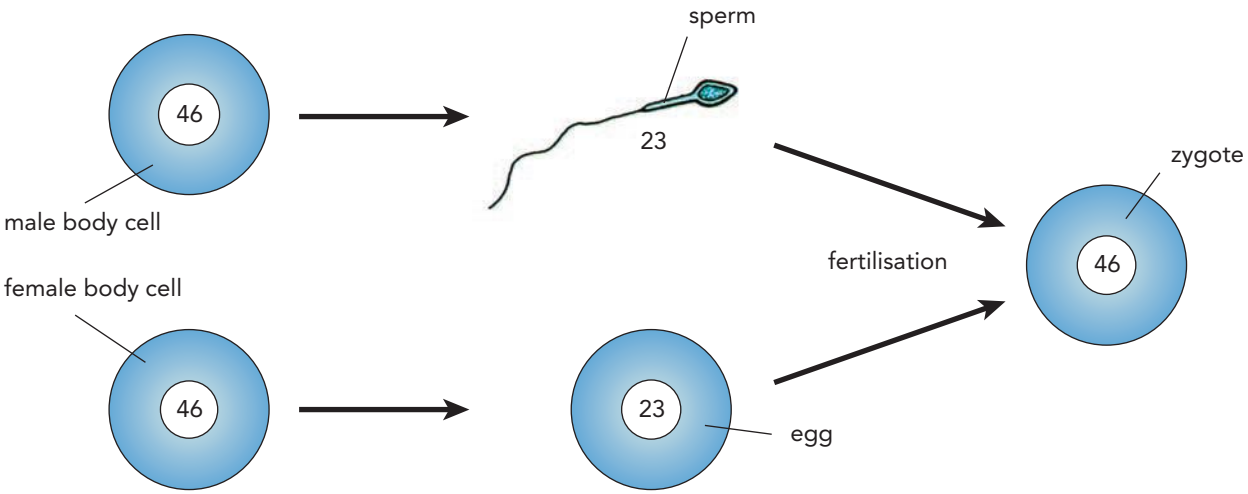

Figure B11.06: Chromosome numbers in sexual reproduction.

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It is important to realise that not all organisms have 46 chromosomes! For example, the cells of a eucalyptus tree have 22 chromosomes. Their male and female gametes each have 11 chromosomes. When these gametes fuse together, they produce a zygote that has 22 chromosomes.

Gametes are made when cells in reproductive organs divide. For example, human sperm are made when cells in a testis divide. The gametes inside pollen grains are made when cells in anthers divide.

Questions

B11.01 The cells in a durian tree have 28 chromosomes. How many chromosomes will there be in a nucleus in an ovule of a durian tree?

B11.02 **a** What is the haploid number of a durian tree?

b What is its diploid number?

Comparing asexual reproduction and sexual reproduction

Many plants, including the strawberries shown at the beginning of this chapter, can reproduce in two ways: asexually and sexually. But which is better?

In asexual reproduction, some of the parent's cells divide by **mitosis**. This makes new cells that are genetically identical to the parent cell. They are clones. Asexual reproduction does not produce genetic variation.

But in sexual reproduction, some of the parent's cells divide by **meiosis**. The gametes that are made have only half as many chromosomes as the parent cell, and the combination of genes on these chromosomes is not the same in every gamete. When two sets of chromosomes in two different gametes combine at fertilisation, a new combination of genes is produced. So sexual reproduction produces offspring that are genetically different from their parents.

KEY WORDS

mitosis: nuclear division giving rise to genetically identical cells in which the chromosome number is maintained by the exact duplication of chromosomes.

meiosis: reduction division in which the chromosome number is halved from diploid to haploid.

Is it useful or not to have genetic variation among offspring? This depends on the circumstances.

Sometimes, it is a good thing not to have any variation. If a plant, for example, is growing well in a particular place, then it is clearly adapted to its environment. If its offspring all inherit the same genes, then they will be equally well adapted and are likely to grow well. This is especially true if there is plenty of space for them in that area. The tulips shown in Figure B11.07 are the products of asexual reproduction.

However, if it is getting crowded, then it may not be a good thing for the parent to produce new offspring that grow all around it. It might be better for them to spread further away. In flowering plants, sexual reproduction produces seeds, which are likely to be dispersed over a wide area. This spreads the offspring far away from the parents, so that they are less likely to compete with them. It also allows them to colonise new areas.

Another advantage of asexual reproduction is that a single organism can reproduce on its own. It does not need to wait to be pollinated, or to find a mate. This can be good if there are not many of those organisms around. Perhaps there is only a single plant growing in an isolated place. In that case, asexual reproduction is definitely the best option. (Do remember, though, that even a single plant may be able to reproduce sexually, by using self-pollination.)

However, if the plant is not doing very well in its environment, or if a new disease has come along to which it is not resistant, then it could be an advantage for its offspring to be genetically different from it. There is a good chance that at least some of the offspring may be better adapted to that environment, or be resistant to that disease. In that case, sexual reproduction would be much more advantageous than asexual reproduction.

You will find out more about variation, and the process of natural selection, in Chapter B13.

Figure B11.07: All the tulips in each row are genetically identical to each other because they have been produced using asexual reproduction. The different varieties of tulips have been produced using sexual reproduction.

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B11.02 Sexual reproduction in plants

Flowers

Many flowering plants can reproduce in more than one way. Often, they can reproduce asexually and also sexually, by means of flowers.

The function of a flower is to make gametes, and to ensure that fertilisation will take place. Figure B11.08 illustrates the structure of an insect-pollinated flower.

The female parts of different kinds of flower vary. One of the differences is the arrangement of the **ovules** in the **ovary**. Figure B11.09 shows one arrangement.

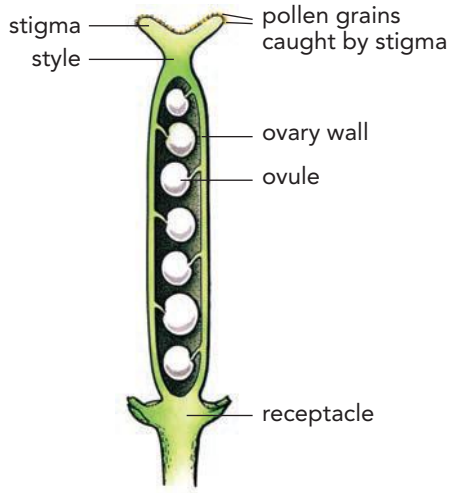
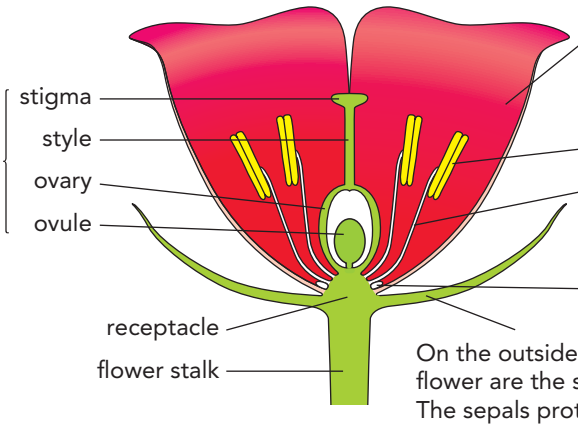


Figure B11.09: Section through the female part (carpel) of a flower.

The female part of the flower is in the centre. It consists of one or more carpels. A carpel contains an ovary. Inside the ovary are many ovules, which contain the female gametes. At the top of the ovary is the style, with a stigma at the tip. The function of the stigma is to catch pollen grains.



Just inside the **sepals** are the petals. These are often brightly coloured. The petals attract insects to the flower.

anther
filament

Inside the petals are the **stamens**. These are the male parts of the flower. Each stamen is made up of a long filament, with an anther at the top. The anthers contain pollen grains, which contain the male gametes.

nectary

On the outside of the flower are the sepals. The sepals protect the flower while it is a bud. Sepals are normally green.

Figure B11.08: The structure of a simple flower.

KEY WORDS

ovules: small structures that contain the female gametes.

ovary: the part of the flower that holds the ovules.

sepals: leaf-like structures that form a ring outside the petals of a flower.

stamens: the male parts of a flower.

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Pollen grains and ovules

The male gametes are inside the pollen grains, which are made in the **anthers**.

Figure B11.10a illustrates a young anther, as it looks before the flower bud opens. You can see in Figure B11.10b that the anther has four spaces inside it, which are called pollen sacs. Some of the cells around the edge of the pollen sacs divide to make pollen grains. When the flower bud opens, the anthers split open (Figure B11.10c). Now the pollen is on the outside of the anther.

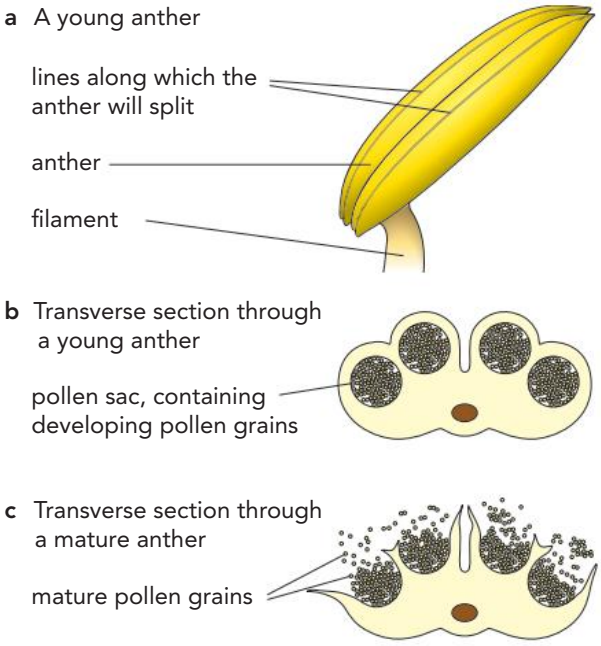

Figure B11.10: How pollen is made.

Pollen looks like a fine powder. It is often yellow. Under the microscope, you can see the shape of individual grains (Figure B11.11). Pollen grains from different kinds of flower have different shapes. Some are spiky, some are smooth. Each grain is surrounded by a hard coat, so that it can survive in difficult conditions if necessary. The coat protects the male gametes that are inside the grains, as the pollen is carried from one flower to another.

The female gametes are inside the ovules, in the ovary (Figure B11.12). Each ovule contains a nucleus. Fertilisation happens when a pollen grain nucleus fuses with an ovule nucleus.

KEY WORD

anther: the structure at the top of a stamen, inside which pollen grains are made.

Figure B11.11: Pollen grains on the surface of an anther of a hibiscus flower. This is a scanning electron micrograph, and the colours are artificial – the pollen is not really purple.

Figure B11.12: A landscape view of a section through the ovary of a daffodil flower. The green part is the wall of the ovary, and you can see part of the short style at the top left. Each little white structure is an ovule, and each ovule contains a nucleus that is a female gamete.

Pollination

For fertilisation to take place, the male gametes must travel to the female gametes. The first stage of this journey is for pollen to be taken from the anther where it was made, to a **stigma**. This is called **pollination**.

Pollination is often carried out by insects (Figure B11.13). Insects such as honeybees come to flowers, attracted by their colour and strong sweet scent. The bee follows guide-lines

KEY WORD

stigma: the part of a flower that receives pollen.

pollination: the transfer of pollen grains from the male part of the plant (anther of stamen) to the female part of the plant (stigma).

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on the **petals** that lead to the nectaries, brushing past the anthers as it goes. Some of the pollen sticks to its body. The bee then goes to another flower, looking for more nectar. Some of the pollen it picked up at the first flower sticks onto the stigma of the second flower when the bee brushes past it. The stigma is sticky, and many pollen grains get stuck on it. If the second flower is from the same species of plant as the first, pollination has taken place.

KEY WORD

petals: coloured structures that attract insects or birds to a flower.

Figure B11.13: The bee has come to the flower to collect nectar. Pollen gets stuck to its body, and the bee will then carry this to the next flower it visits.

ACTIVITY B11.01

Investigating the structure of a flower

Work with a partner for this activity. You will need a flower, and perhaps also some transparent sticky tape.

Look carefully at a simple flower – one that has a ring of petals, surrounding some anthers and ovaries.

Using Figure B11.08, identify each part of the flower.

Now take off the outer ring of flower parts – the sepals. You can stick them into your book if you like. Even better, you could construct a table with three columns. Name the part in the first column, stick the part into the second column, and write a description of its function in the third column.

Work your way through to the centre of the flower, removing each ring of flower parts in turn.

Reflection

Do you find that doing something active, such as taking apart a real flower, helps you to understand it better than just looking at a flower or a picture of one? If you do, think about how you could use some kind of activity to try to help your brain to understand and remember other topics.

Wind pollination

In some plants, it is the wind which carries the pollen between flowers. Figure B11.14 shows a grass flower, which is an example of a wind-pollinated flower. Figure B11.15 shows pollen grains from a grass flower. You can see how smooth they are, compared with the spiky pollen grains in Figure B11.11.

Wind-pollinated flowers usually produce much more pollen than insect-pollinated flowers. This is because a lot of the pollen does not land on another flower, so huge amounts are wasted. Although insects do eat some pollen, they are still much more likely than the wind to deliver pollen successfully to another flower.

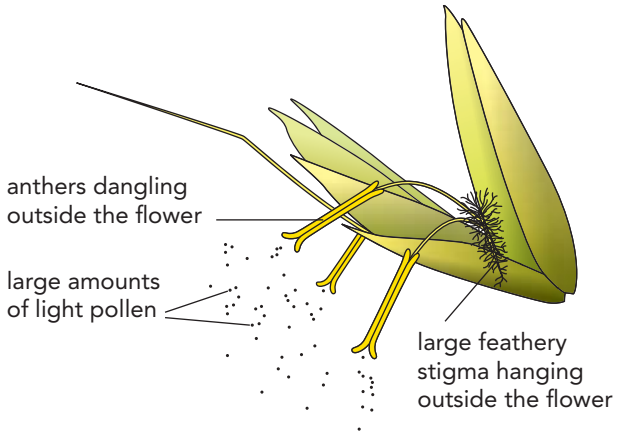

Figure B11.14: A grass flower: an example of a wind-pollinated flower.

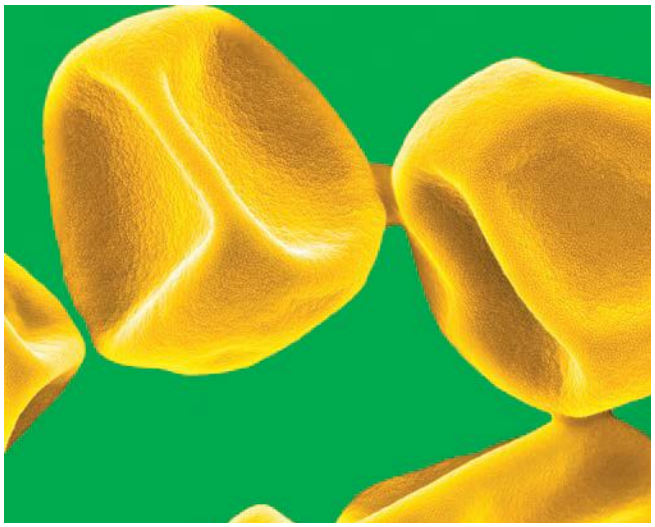

Figure B11.15: Pollen grains from a grass flower. These small, smooth grains are adapted to be carried easily by the wind.

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Insect-pollinated flower	Wind-pollinated flower
large, conspicuous petals, often with guide-lines	small, inconspicuous petals, or no petals at all
often strongly scented	no scent
often have nectaries at the base of petals	no nectaries
anthers inside flower, where insect has to brush past them to reach nectar	anthers dangle outside the flower, where they catch the wind
stigma inside flower, where insect has to brush past it to reach nectar	stigmas large and feathery and dangle outside the flower, where pollen in the air may land on them
sticky or spiky pollen grains, which stick to insects	smooth, light pollen, which can be blown in the wind
quite large quantities of pollen made, because some will be eaten or will be delivered to the wrong kind of flower	very large quantities of pollen made, because most will be blown away and lost

Table B11.01: A comparison between insect-pollinated and wind-pollinated flowers.

The anthers and stigmas of wind-pollinated flowers dangle outside the flower, to catch the wind.

These flowers usually do not have petals, as there is no need to attract insects. The filaments of the anthers are very flexible, so they can swing in the wind and release their pollen. The feathery stigmas have a large surface area, increasing the chances of catching pollen. In contrast, insect-pollinated flowers have anthers and stigmas that are enclosed within the petals, so that insects have to brush past them to reach the nectar.

Table B11.01 compares insect-pollinated and wind-pollinated flowers.

Questions

B11.03 Figure B11.16 shows a bee visiting a flower.

Describe how the flower is adapted to make sure that bees will visit it, and also that the bees will pick up pollen and deposit it in the right place.

B11.04 Figure B11.17 shows some grass flowers.

a Explain how these flowers are adapted for wind pollination.

b Many people suffer from an allergy to pollen, called hay fever. They are usually more badly affected by grass pollen than by pollen from insect-pollinated flowers. Suggest why.

Figure B11.16: A bee visiting a flower.

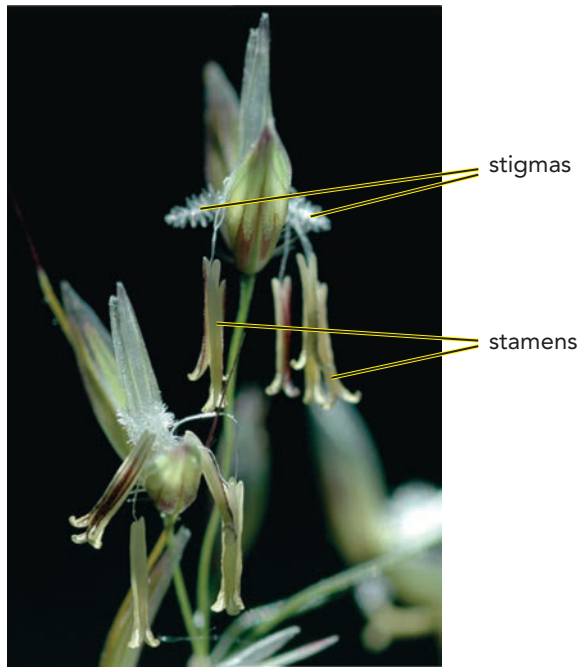

Figure B11.17: Grass flowers.

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Fertilisation

After pollination, the male gamete inside the pollen grain is on the stigma. It still has not reached the female gamete. The female gamete is inside the ovule, and the ovule is inside the ovary. For fertilisation to take place, the male gamete (a nucleus inside a pollen grain) must fuse with a female gamete (a nucleus inside an ovule).

Seeds

After the ovules have been fertilised, many of the parts of the flower are not needed any more. The sepals, petals and stamens have all done their jobs. They wither (dry and shrink) and fall off.

Inside the ovary, the ovules start to grow. Each ovule now contains a zygote, which was formed at fertilisation. The zygote divides by mitosis to form an embryo plant. The ovule is now a **seed**.

A seed contains very little water. When the seed was formed on the plant, the water in it was drawn out, so that the seed became dehydrated. Without water, almost no metabolic reactions can go on inside it. The seed is **dormant**. This is very useful, because the dormant seed can survive harsh conditions, such as cold or drought, which would kill a growing plant.

A seed must be in certain conditions before it will begin to germinate. You can find out what they are in the following investigation.

KEY WORDS

seed: the structure that develops from an ovule after fertilisation; it contains an embryo plant.

dormant: inactive, with metabolic reactions taking place very slowly or not at all.

EXPERIMENTAL SKILLS B11.01

Investigating the conditions necessary for the germination of seeds

In this investigation, you will provide several sets of seeds with different combinations of conditions. This will enable you to work out which conditions they need before they will germinate. You will also practise constructing and completing a results table.

You will need:

- at least 50 small seeds, e.g. mustard seeds or tomato seeds
- the apparatus shown in Figure B11.18.

Safety

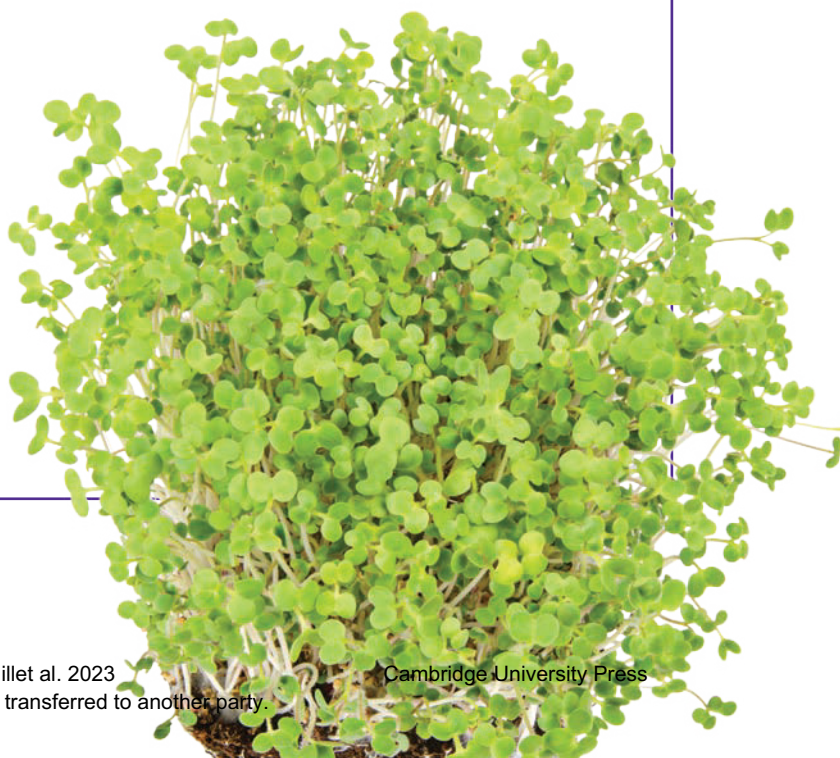
Wear safety spectacles at all times. Do not eat or drink in the laboratory.

Method

1. Set up five large test-tubes, as shown in Figure B11.18. If there is no suitable dark place to leave tubes B and C, you can cover the tubes with black paper instead. Make sure that you put the same number of seeds into each tube.
2. Check the tubes each day. Count how many seeds have germinated, and record this as a percentage in a results table.
3. Use your results to decide which conditions these seeds require, in order to germinate.

Questions

1. Most seeds need water, oxygen and a warm temperature before they will germinate. (You probably found that your seeds needed these conditions.) When a seed germinates, there is a lot of metabolic activity inside the seed. Suggest why these three conditions are required for germination.
2. Although many seeds do not need light for germination, some do. For example, seeds of trees that grow in tropical rainforests will often only germinate if they have a lot of light. This could happen, for example, if a large tree fell over, leaving a gap in the forest. Suggest the advantage to these seeds of germinating only when they have light.



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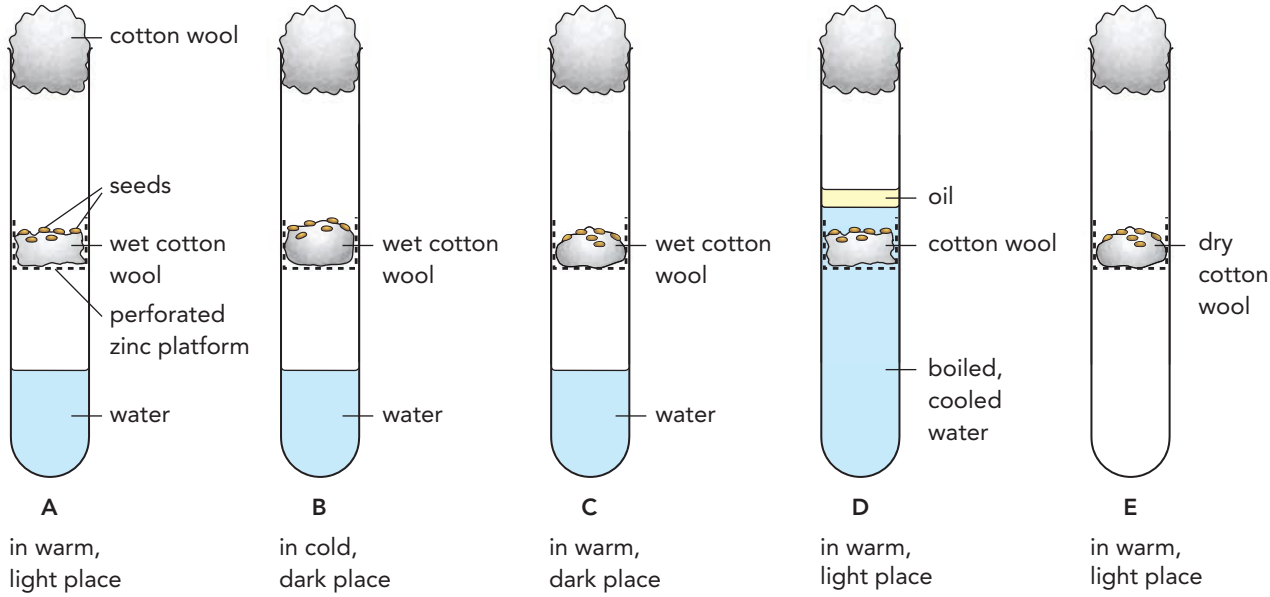

Figure B11.18: Apparatus for Experimental skills B11.01.

Self assessment

How satisfied are you with the results table that you constructed?

Does it clearly show the conditions in each tube?

Does it clearly show the percentage of seeds that germinated in each tube?

Is it easy to see quickly which conditions produced the highest percentage germination?

B11.03 Sexual reproduction in humans

Humans, like all mammals, reproduce sexually. A new life begins when the nucleus of a male gamete fuses with a female one, forming a zygote. This is how every human being is formed.

The female reproductive organs

Figure B11.19 shows the reproductive organs of a woman. The female gametes, called eggs or egg cells, are made in the two **ovaries**. Leading away from the ovaries are the **oviducts**, sometimes called Fallopian tubes. The tubes do not connect directly to the ovaries but have a funnel-shaped opening just a short distance away.

KEY WORDS

ovaries: organs that produce female gametes (eggs).

oviducts: tubes leading from the ovaries to the uterus; also known as Fallopian tubes.

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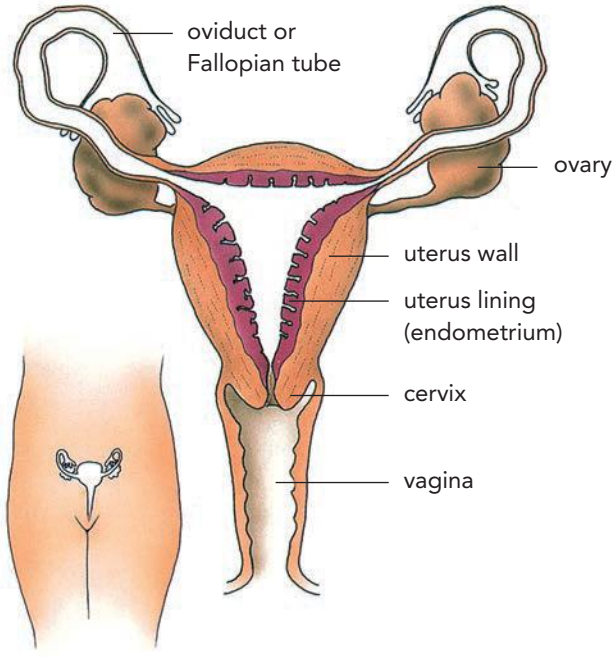

Figure B11.19: The female reproductive organs.

The two oviducts lead to the womb or **uterus**. This has very thick walls, made of muscle. It is quite small – only about the size of a clenched fist – but it can stretch a great deal when a woman is pregnant.

At the base of the uterus is a narrow opening, guarded by muscles. This is the neck of the uterus, or **cervix**. This narrow opening connects to the **vagina**, which then leads to the outside of the body.

The opening from the bladder, called the urethra, is a tube that is in front of the vagina, while the rectum is just behind it. These three tubes open quite separately to the outside.

The male reproductive organs

Figure B11.20 shows the reproductive organs of a man. The male gametes, called spermatozoa or sperm, are made in two **testes** (singular: **testis**). These are outside the body, in two sacs of skin called the **scrotum**.

The sperm are carried away from each testis in a tube called the **sperm duct**. The sperm ducts from the testes join up with the urethra just below the bladder. The urethra continues downwards and opens at the tip of the **penis**. The urethra can carry both urine and sperm at different times.

KEY WORDS

uterus: the organ in which a fetus develops before birth; also known as the womb.

cervix: a narrow opening leading from the uterus to the vagina.

vagina: opening from the uterus to the outside of the body.

testes (singular: testis): organs in which the male gametes (sperm) are made.

scrotum: the sac that contains the testes.

sperm duct: a tube that transports sperm from the testis to the urethra.

penis: organ containing the urethra, through which urine and sperm are carried.

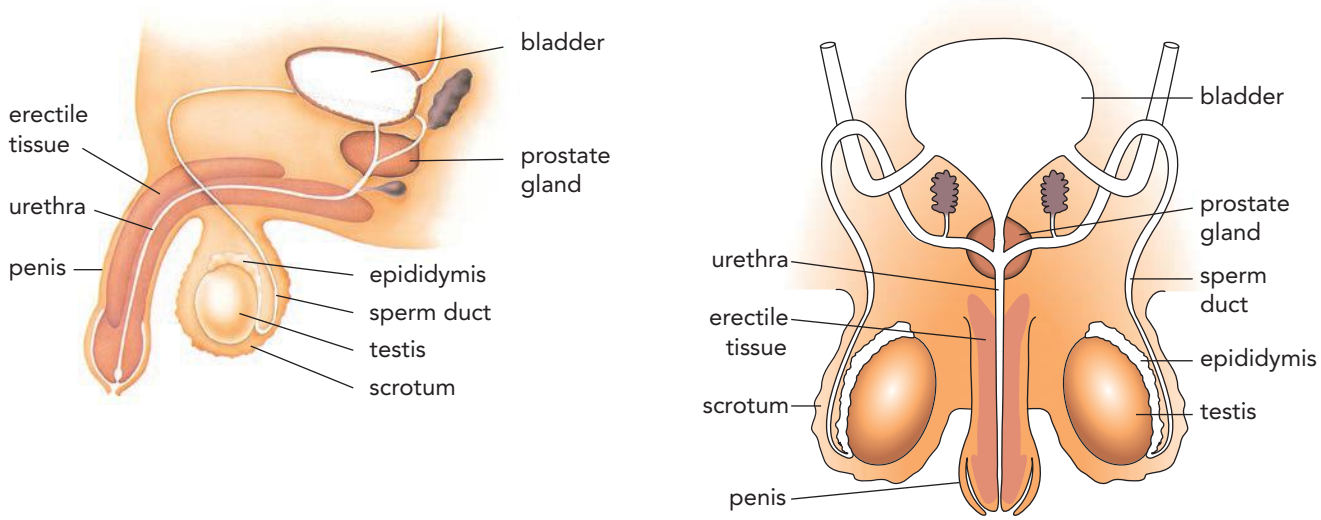

Figure B11.20: a Side view of the male reproductive organs. **b** Front view of the male reproductive organs.

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Where the sperm ducts join the urethra, there is a gland called the **prostate gland**. This makes a fluid called semen, which the sperm swim in.

KEY WORDS

prostate gland: organ that produces a nutritious fluid in which sperm are transported.

Human gametes

Eggs begin to be formed inside a girl's ovaries before she is born. At birth, she will already have thousands of partly developed eggs inside her ovaries.

When she reaches puberty (described later in this topic), some of these eggs begin to mature. Usually, only one develops at a time.

An egg is a single cell. Figure B11.21 shows the structure of an egg cell. When it is fully developed, it bursts out of the ovary and into the funnel at the end of the oviduct. This is called **ovulation**. In humans, it happens once a month throughout a woman's reproductive life.

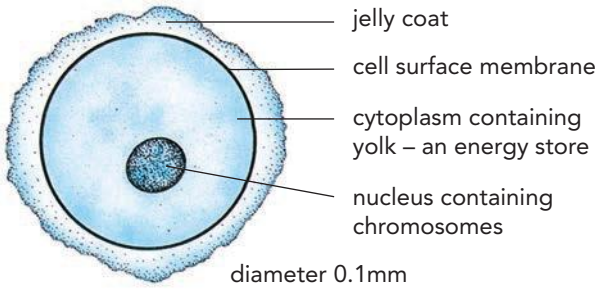

Figure B11.21: A human egg cell.

Figure B11.22 shows the structure of a sperm and describes how it is adapted for its function of fertilising an egg.

Eggs and sperm are **haploid** cells. Each human egg and each human sperm has a single set of 23 chromosomes in its nucleus. Eggs and sperm are made when cells in the ovaries and testes divide by meiosis. When their nuclei fuse (join) together during fertilisation, the cell they form, called a **zygote**, is **diploid**. This means that it has two sets of chromosomes in its nucleus. In humans, this consists of 46 chromosomes.

KEY WORDS

ovulation: the release of an egg from an ovary.

haploid (nucleus): a nucleus containing a single set of unpaired chromosomes (e.g. in sperm and egg cells)

diploid (nucleus): a nucleus containing two sets of chromosomes (e.g. in body cells)

zygote: the diploid cell produced when two gametes fuse

Fertilisation

After ovulation, the egg is caught in the funnel of the oviduct. Very slowly, the egg travels towards the uterus. Cilia lining the oviduct help to sweep it along. Muscles in the wall of the oviduct also help to move it, by producing gentle rippling movements.

If the egg is not fertilised by a sperm within 8–24 hours after ovulation, it dies. By this time, it has only travelled a short way along the oviduct. This means that a sperm must reach an egg while it is quite near the top of the oviduct if fertilisation is to be successful.

To bring the sperm as close as possible to the egg, the man's penis is placed inside the vagina of the woman. Sperm travel out of the penis into the vagina. This happens when muscles in the walls of the tubes containing the sperm contract rhythmically. The wave of contraction begins in the testes, travels along the sperm ducts, and into the penis. The sperm are squeezed along the tubes, out of the man's urethra and into the woman's vagina.

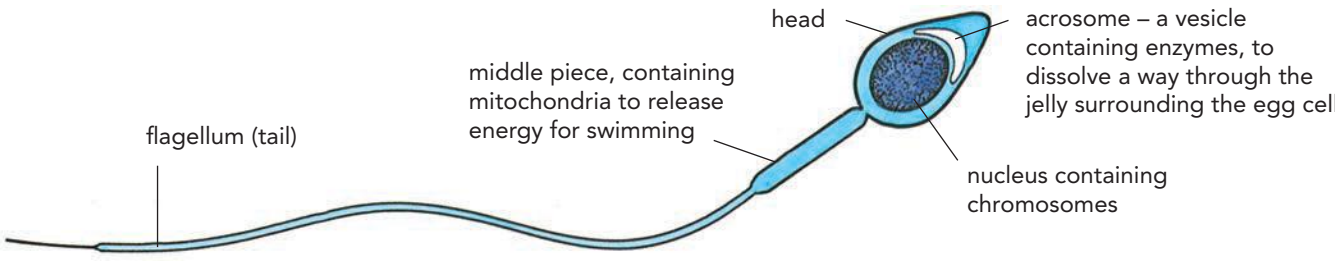

Figure B11.22: A human sperm. Sperm are motile (can move) and have adaptations to help them to swim.

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The fluid containing the sperm is called semen. The liquid part of semen is produced by the prostate gland. It contains sugars and other nutrients to provide the sperm with energy. The semen is deposited at the top of the vagina, near the cervix.

The sperm are still quite a long way from the egg. They swim – using their **flagella** (singular: **flagellum**) and energy released in their mitochondria – up through the cervix, through the uterus, and into the oviduct (Figure B11.23).

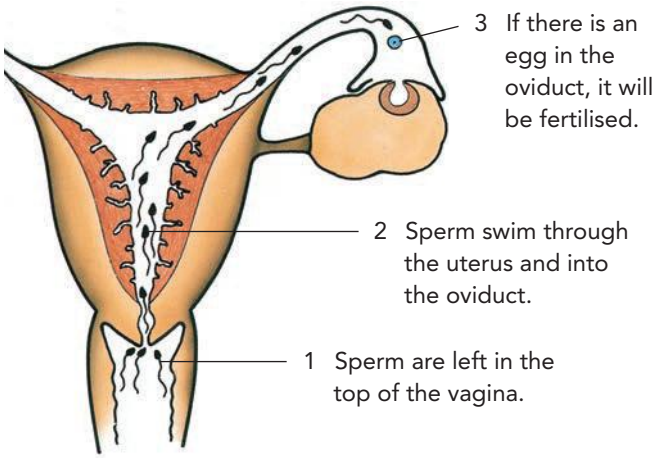

Figure B11.23: The route taken by sperm to get to an egg. The sperm are shown many times bigger than they really are, in relation to the female reproductive organs.

Sperm can only swim at a rate of about 4 mm per minute, so it takes quite a while for them to get as far as the oviducts. Many will never get there at all. But about a million sperm are deposited in the vagina at once, so there is a good chance that some of them will reach the egg to achieve fertilisation.

When a sperm cell contacts the jelly coat surrounding an egg cell, the **acrosome** is activated. It releases its digestive enzymes, and these enzymes digest the jelly coat. This allows the head of the sperm to push through and get into the cytoplasm of the egg. Only the head of the sperm goes in; the flagellum is left outside. The nucleus of the sperm fuses with the nucleus of the egg. This is fertilisation (Figure B11.24).

KEY WORDS

flagella (singular: flagellum): a long, whip-like 'tail' structure found on sperm cells, used for swimming.

acrosome: a structure containing digestive enzymes, in the head of a sperm cell.

As soon as the successful sperm enters the egg, the egg membrane and jelly coat become impenetrable, so that no other sperm can get in. The unsuccessful sperm will all die.

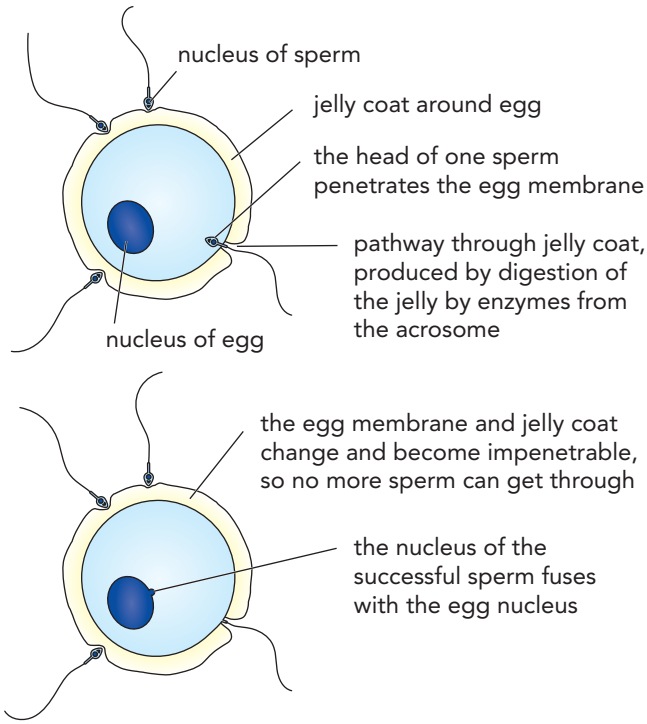

Figure B11.24: Fertilisation.

Questions

B11.05 State precisely where eggs and sperm are made in a human.

B11.06 Copy and complete each of these sentences.

- **a** The liquid part of semen is produced in _____.
- **b** Fertilisation happens in _____ .
- **c** Implantation happens in _____ .

B11.07 Construct a table to compare the structure of an egg and a sperm. Include a column which explains the reason for each difference.

B11.08 Before fertilisation happens, both sperm and eggs are moving. Describe the differences in the way that the two types of gamete move.

Testosterone and oestrogen

The functions of the reproductive organs are strongly affected by hormones. The main reproductive hormone produced in men is testosterone, while in women oestrogen and progesterone are secreted.

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The time when a person approaches sexual maturity is called adolescence. Sperm production begins in a boy, and ovulation begins in a girl. The point at which sexual maturity is reached is called **puberty**. This is often a few years earlier in girls than in boys. A person is still not completely adult at this point, as there are still changes and development happening in the brain.

KEY WORD

puberty: the time at which sexual maturity is reached.

The changes that happen during adolescence are brought about by hormones. In boys, testosterone is secreted by the testes. During adolescence, the quantity of testosterone that is secreted greatly increases, and this causes the secondary sexual characteristics to develop. These include growth of facial hair and pubic hair, broadening of the shoulders and general muscular development, and a deepening voice.

In girls, oestrogen is secreted by the ovaries. It causes the breasts to grow larger, pubic hair to grow, and the hips to become wider.

The menstrual cycle

Eggs develop in small structures called **follicles**, in the ovaries. After a girl reaches puberty, one egg is usually released from a follicle into the oviduct every month. Before the egg cell is released, the lining of the uterus becomes thick and spongy, so that it is ready to receive a zygote. It is full of tiny blood vessels, which will supply the embryo with nutrients and oxygen if it should arrive.

However, if the egg cell is not fertilised, the spongy lining is not needed. It gradually breaks down and is slowly lost through the vagina. This is called **menstruation**, or a period. It usually lasts for about five days. After menstruation, the lining of the uterus builds up again, so that it will be ready to receive the next egg, if it is fertilised.

Figure B11.25 shows what happens during the human menstrual cycle.

KEY WORDS

follicle: a structure within an ovary, in which an egg develops.

menstruation: the loss of the broken down uterus lining through the vagina.

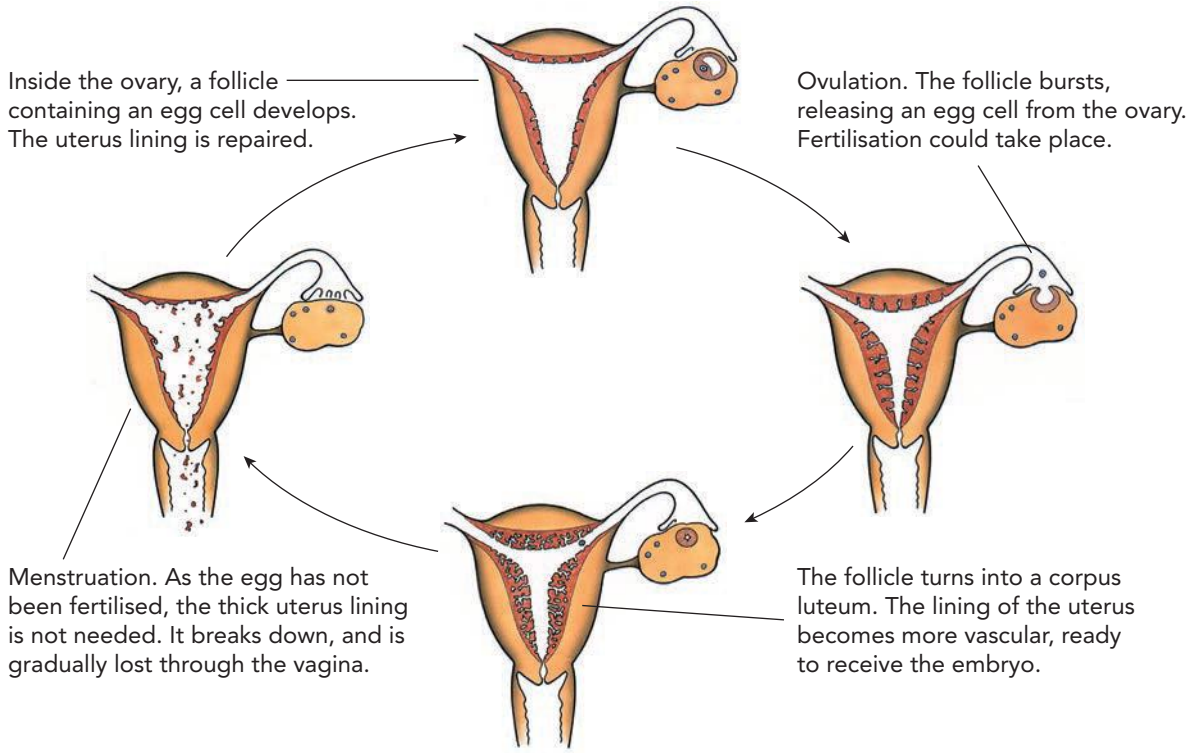

Figure B11.25: The menstrual cycle.

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Questions

B11.09 State *one* function of testosterone, and *one* function of oestrogen.

B11.10 Describe what is happening in an ovary during the menstrual cycle, when each of these events is happening in the uterus:

- **a** The uterus lining is breaking down.
- **b** The uterus lining is building up again.
- **c** The uterus lining is remaining thick and well supplied with blood.

B11.04 Sexually transmitted infections

Sexually transmitted infections (STIs) are infections caused by bacteria or viruses that can be passed from one person to another during sexual contact. One example of these infections is HIV/AIDS.

The disease **acquired immune deficiency syndrome (AIDS)** is caused by the **human immunodeficiency virus (HIV)**. Figure B11.26 shows this virus.

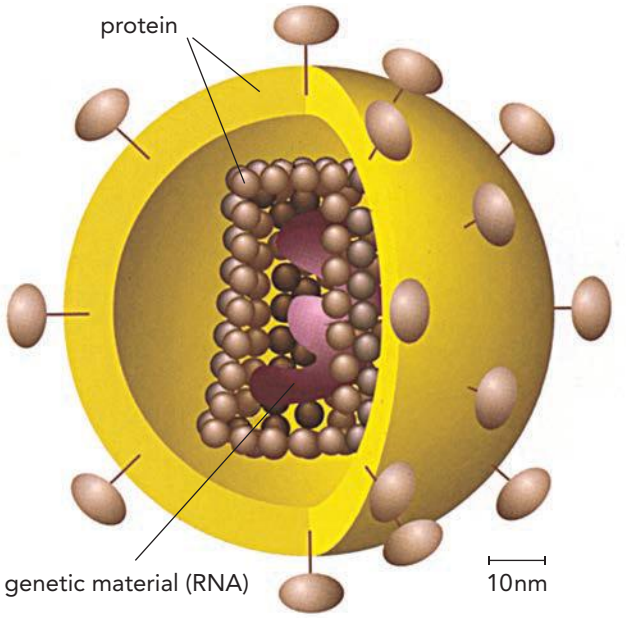

Figure B11.26: The human immunodeficiency virus, HIV. The letters nm stand for nanometre, and there are 10^6 nanometres in one millimetre.

KEY WORDS

sexually transmitted infection (STI): a disease caused by pathogens that are transmitted during sexual contact.

acquired immune deficiency syndrome (AIDS): a disease caused by the human immunodeficiency virus (HIV).

human immunodeficiency virus (HIV): a virus which destroys white blood cells and, therefore, reduces the ability of the immune system to defend against other pathogens.

HIV infects white blood cells, and in particular a type called T cells. Over a long period of time, HIV slowly destroys T cells. Several years after infection with the virus, the numbers of certain kinds of T cells are so low that they are unable to fight against other pathogens effectively.

T cells are normally our strongest defence against viruses. Because HIV attacks the very cells which would normally kill viruses, it is very difficult for someone's own immune system to protect them against HIV.

About ten years after initial infection with HIV, an untreated person is likely to develop symptoms of AIDS. They become very vulnerable to other infections, such as pneumonia. They may develop cancer, because one function of the immune system is to destroy body cells that may be beginning to produce cancers. Brain cells are also quite often damaged by HIV. A person with AIDS usually dies from a collection of several illnesses.

Today, however, there are excellent drugs to control HIV. These drugs are called antiretrovirals. They stop the virus from multiplying inside the person's cells. A person who takes these regularly is likely to live a healthy and normal life.

Researchers are working on the production of a vaccine against HIV infection, and there have been promising signs in early trials. By the time you read this, perhaps a vaccine will have become available.

Preventing HIV transmission

The virus that causes AIDS cannot live outside the human body. In fact, it is an especially fragile virus – much less tough than the cold virus, for example.

In general, there is no danger of anyone becoming infected with HIV from normal contact with someone with AIDS. You can quite safely talk to the person, shake hands with them, drink from cups which they have used and so on.

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A person can only become infected with HIV through direct contact of their body fluids with those of someone with the virus. A person with HIV is said to be HIV positive. A person can become HIV positive in one of the following ways.

Through sexual contact

HIV can live in the fluid inside the vagina, rectum and urethra. During sexual intercourse, fluids from one partner come into contact with fluids of the other. It is very easy for the virus to be passed on in this way.

The more sexual partners a person has, the higher the chance of them becoming infected with HIV. Higher percentages of people have developed AIDS where it is common to have multiple sexual partners.

The best way of avoiding AIDS is never to have more than one sexual partner. If everyone did that, then HIV would immediately stop spreading. Using a condom (a sheath that covers the penis and prevents semen from escaping) is a good way of lowering the chances of the virus passing from one person to another during sexual intercourse. However, it does not offer complete protection.

It is also important that anyone who is infected with HIV knows that they have this virus in their body, so that they can avoid passing it on to anyone else. If someone discovers that they are HIV positive, health workers will try to trace the people who they could have passed the infection on to, and make sure that they are all tested for the virus. This can reduce the spread of HIV through a population.

Through blood contact

Many cases of AIDS have been caused by HIV being transferred directly from one person's blood to another. In the 1970s and 1980s, when AIDS first appeared, and before anyone knew what was causing it, blood containing HIV was used in transfusions. People being given the transfusions were infected with HIV, and later developed AIDS. Now all blood used in transfusions in most countries is screened for HIV before it is used.

The virus can also pass from an infected mother to her child during childbirth, when the blood of the mother comes into contact with the baby. The chance of this happening is greatly reduced if the mother takes antiretroviral drugs during her pregnancy.

Blood can also be transferred from one person to another if they share hypodermic needles. This most commonly happens in people who inject drugs. Many drug users have died from AIDS. It is essential that any hypodermic needle used for injection is sterile. People who have to deal with accidents, such as police and paramedics, must always be on their guard against HIV if there is blood around. They often wear protective clothing, just in case a bleeding accident victim is infected with HIV.

Through breast feeding

If a woman is infected with HIV, the virus can get into her breast milk and so be passed on to her baby. The chance of this happening is greatly reduced if the mother takes antiretroviral drugs during her pregnancy and while breast feeding.

ACTIVITY B11.02

Breast feeding or not?

Work in a group of two or three for this activity.

In some countries, mothers who are HIV positive are advised not to breast feed their babies, but instead to feed them with formula milk in a bottle. In other countries, the advantages of breast feeding are considered to outweigh the risk of passing on HIV.

In your group, discuss why the advice may be different in different countries.

Listen to the ideas from other groups, and also share your own group's ideas.

Write a short summary of the possible reasons your class has thought of, to explain why the advice given in different countries may not be the same.

Self assessment

How well did you work with your group? Did you:

- contribute by giving your own points of view?
- listen to other people's points of view?
- think carefully about these, even if you did not agree with them to begin with?

Reflection

Linking different parts of the syllabus can be tricky, but it can help you to understand each part a little better. How well do you think that you reviewed the plant reproduction topic, so that you could link it to human reproduction? Did you find that doing this helped you to understand the two topics better than you did before tackling this project? If so, can you see ways in which you could use a similar approach for increasing your understanding of other topics?

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PROJECT B11.01 COMPARING PLANT AND HUMAN REPRODUCTION

You are going to work with a partner or in a group of three, to produce a presentation or display about the similarities and differences between flowering plant reproduction and human reproduction.

Are there any similarities in the way that humans and plants reproduce?

Begin by brainstorming ideas. On two pieces of paper, or two pages in your notebook, write the headings 'Similarities' and 'Differences'.

Write down anything you can think of that fits into those two categories. Some of them will be quite general. For example, plants can reproduce both asexually and sexually, but humans can reproduce only sexually. Others may be more specific, such as a comparison of the structures of the gametes, or how fertilisation takes place.

When you have your list, think about how you will organise the points and how you will present and/or display your comparison. You should be able to come up with several ideas, and then decide on the best one. It would be excellent if different groups in your class use different ways of presenting their comparisons.

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SUMMARY

Asexual reproduction involves a single parent and produces genetically identical offspring. Sexual reproduction may involve one or two parents, which produce gametes. The nuclei of the gametes fuse in the process of fertilisation, producing genetically different zygotes.
In flowering plants, male gametes are found inside pollen grains and female gametes inside ovules.
Gamete nuclei have one set of chromosomes and are said to be haploid. Body cells have two sets of chromosomes and are diploid.
An insect-pollinated flower has petals to attract insects. The insects pick up pollen grains from the anthers and deposit them on a stigma.
Wind-pollinated flowers generally do not have petals. They have anthers and feathery stigmas that dangle outside the flower, so that pollen can easily be blown away by the wind, and land on a stigma.
Insect-pollinated flowers produce relatively small quantities of sticky or spiky pollen. Wind-pollinated flowers produce very large quantities of smooth, lightweight pollen.
Fertilisation happens when a pollen nucleus fuses with a nucleus in an ovule.
After fertilisation, an ovule becomes a seed. Seeds can only germinate when they have water, oxygen and a suitable temperature.
Asexual reproduction is useful to a species of plant that is well adapted to its current environmental conditions, or when there are not many other plants available that it could exchange gametes with. Sexual reproduction is useful to a species of plant that will benefit from genetic variation, such as to adapt to changing environmental conditions.
The male reproductive system consists of the testes, scrotum, sperm ducts, prostate gland, urethra and penis.
Sperm are made and stored in the testes, which are enclosed in the scrotum. Sperm ducts carry sperm to the urethra in the penis. The prostate gland makes a liquid in which sperm are carried, forming semen.
The female reproductive system includes the ovaries, oviducts, uterus, cervix and vagina.
Eggs are made in the ovaries and released into the oviducts.
Sperm are motile. They have a flagellum which is used for swimming; many mitochondria to release energy by aerobic respiration; and an acrosome containing enzymes to help them enter an egg.
Eggs have a jelly coat to control the entry of sperm, and nutrient stores to provide energy for the first few days after fertilisation.
Sperm are produced in much larger numbers than eggs. Unlike eggs, sperm can swim actively, and they are much smaller than eggs.
Fertilisation happens when the nucleus of a sperm fuses with the nucleus of an egg. A sperm cell releases enzymes from its acrosome. These enzymes digest a pathway through the jelly coat of the egg, allowing the sperm head to enter the egg. The entry of the sperm head causes a change in the egg membrane and jelly coat, preventing more sperm entering.
Testosterone is secreted by the testes and causes the development of male secondary sexual characteristics during puberty. Oestrogen is secreted by the ovaries and causes the development of female secondary sexual characteristics.
During the first five days of the menstrual cycle, the lining of the uterus breaks down and is lost through the vagina. At about day 11, an egg is released from an ovary. After this, the follicle from which the egg came changes into a corpus luteum. The cycle lasts about 28 days, after which it begins again.
STIs, such as HIV/AIDS, are transmitted through sexual contact.
HIV is a viral pathogen that causes AIDS. It can be transmitted by sexual contact, direct blood-to-blood contact, or through breast feeding. Tracing contacts, using condoms, using antiretroviral drugs and avoiding sharing needles can help to reduce its spread.

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PRACTICE QUESTIONS

1 Sexual reproduction involves the fusion of the nuclei of gametes.
Identify what is produced.

A zygotes **B** seeds

C ovules **D** flowers **[1]**

2 Identify why it is almost impossible for more than one sperm to fertilise an egg.

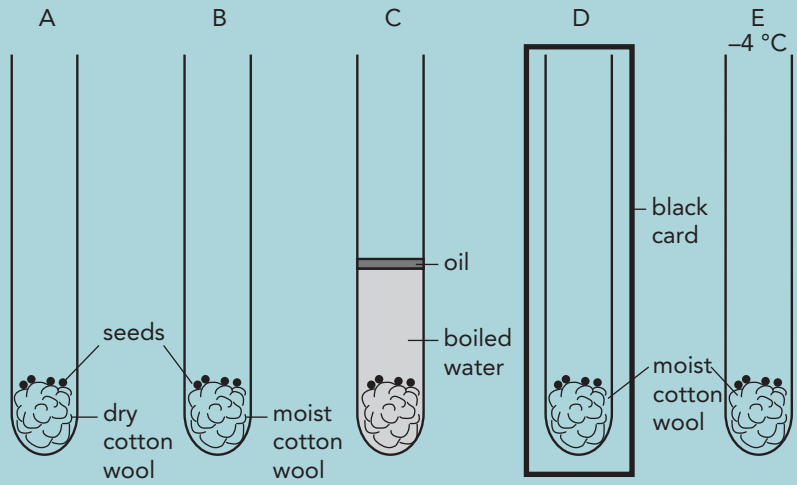
A The jelly coat thickens after one sperm has entered the egg.

B There is not enough space for more than one sperm inside the egg.

C The sperm change after fertilisation, so their acrosomes do not function.

D The sperm stop swimming once one of them has entered the egg. **[1]**

3 A student investigated the conditions that mustard seeds need, in order to germinate. The diagram shows the apparatus he used.



a Place ticks (✓) in the table to identify the environmental conditions present in each tube.

The first row has been done for you. **[2]**

	Tube				
	A	B	C	D	E
Water	✗	✓	✓	✓	✓
Oxygen					
Warm temperature					
Light					

b Mustard seeds require water, a warm temperature and oxygen in order to germinate. **Predict** the tubes in which the seeds will germinate. **[2]**

c Seeds are produced after fertilisation happens in a flower.

i **Describe** what happens during fertilisation in a flower. **[2]**

ii **Give** the name of the part of a flower that develops into a seed, after fertilisation. **[1]**

[Total: 7]

COMMAND WORD

identify: name/select/recognise.

COMMAND WORDS

predict: suggest what may happen based on available information.

describe: state the points of a topic/give characteristics and main features.

give: produce an answer from a given source or recall/memory.

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CONTINUED

4 The diagram below shows a banana plant producing suckers.

a Give the name of the type of reproduction that is shown in the diagram. **[1]**

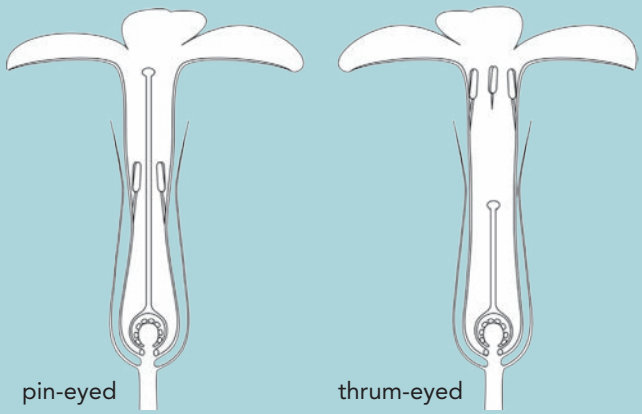
b Describe the advantage to the growers of banana plants of using this type of reproduction to propagate their plants. **[2]**

c Banana plants can be killed by fungal diseases, such as black sigatoka and Panama disease.

Explain why a population of bananas produced by the method shown in the diagram could all be killed by the same disease. **[2]**

[Total: 5]

5 The diagram below shows two types of primrose flower.



These types of flower are often found growing close together.
Any one primrose plant, however, only has one type of flower.

a Describe the difference in the arrangement of the anthers and stigmas in the pin-eyed and thrum-eyed primrose. **[2]**

b Primroses are pollinated by insects, which reach into the bottom of the flower to get nectar. **Identify** the part of the insect's body that would pick up pollen in:

i a pin-eyed primrose **[1]**

ii a thrum-eyed primrose. **[1]**

COMMAND WORD

explain: set out purposes or reasons/make the relationships between things evident/provide why and/or how and support with relevant evidence.

COMMAND WORD

identify: name/select/recognise.

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CONTINUED

c Identify the part of the insect's body that would touch the stigma in:

i a pin-eyed primrose [1]

ii a thrum-eyed primrose. [1]

[Total: 6]

6 These questions are about the parts of the male reproductive system.

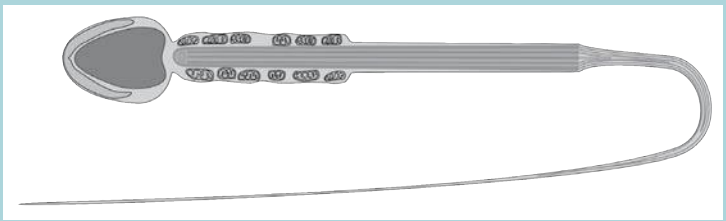
a Give the name of the tube that allows sperm to pass out of the body. [1]

b Give the name of the gland that produces a fluid that mixes with the sperm. [1]

c Give the name of the hormone made by the testes. [1]

[Total: 3]

7 This diagram shows a human sperm.



a Label the following parts:

cell membrane **cytoplasm** **nucleus**

mitochondrion **flagellum** **acrosome** [3]

b With reference to your diagram, explain how the structure of a sperm adapts it for its function. [4]

c Describe how a human egg cell is adapted for its function. [3]

[Total: 10]

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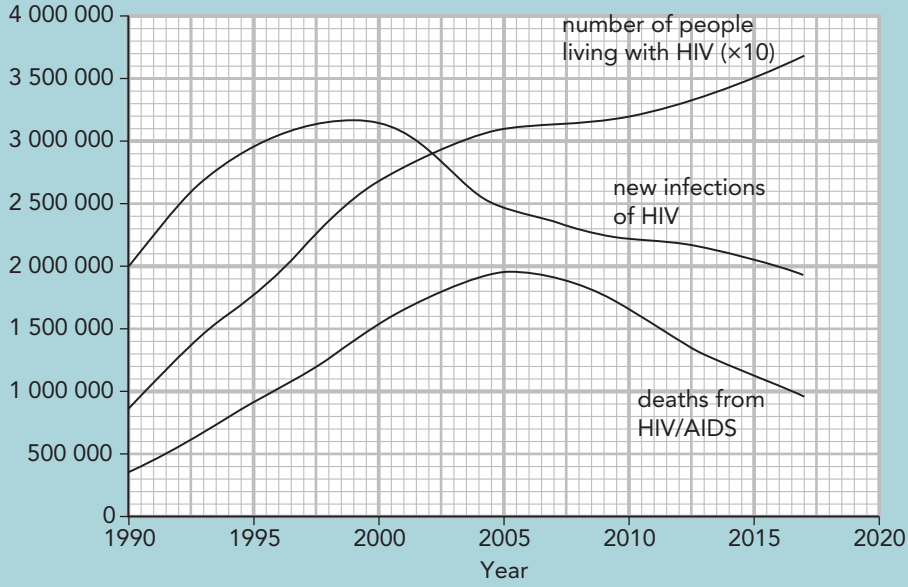
CONTINUED

8 The graph below shows the number of people in the world who became infected with HIV, who were living with HIV/AIDS and who died from AIDS, between 1990 and 2017. Note that, to **calculate** the numbers of people living with HIV, you have to multiply the number on the *y*-axis scale by 10.



a With reference to the graph, describe the changes in the number of new infections of HIV. **[3]**

b **Suggest** why the actual number of people infected with HIV could possibly be greater than the numbers shown on the graph. **[2]**

c Explain how infection with HIV leads to the symptoms of AIDS. **[5]**

d **Compare** the trends shown by the number of people living with HIV/AIDS with the number of deaths from HIV/AIDS. Suggest reasons for the differences that you describe. **[5]**

[Total: 15]

COMMAND WORD

calculate: work out from given facts, figures or information.

COMMAND WORDS

suggest: apply knowledge and understanding to situations where there is a range of valid responses in order to make proposals/put forward considerations.

compare: identify/comment on similarities and/or differences.

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SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
describe asexual reproduction as a process that produces genetically identical offspring from one parent	B11.01			
describe sexual reproduction as a process that involves fertilisation (the fusion of gamete nuclei), forming zygotes that are genetically different from one another	B11.01			
explain what is meant by the terms *haploid* and *diploid*, and state that gametes are haploid, and zygotes are diploid	B11.01			
compare the advantages and disadvantages of sexual reproduction and asexual reproduction, to a population of a species living in the wild	B11.01			
identify these parts on photographs or specimens of insect-pollinated flowers: sepals, petals, stamens, filaments, anthers, carpels, styles, stigmas, ovaries and ovules	B11.02			
explain the functions of all of the parts of an insect-pollinated flower	B11.02			
compare the structures of insect-pollinated and wind-pollinated flowers, including differences between their pollen grains	B11.02			
describe how pollination takes place	B11.02			
state that fertilisation in a flower happens when a nucleus from a pollen grain fuses with a nucleus in an ovule	B11.02			
investigate and describe the conditions that seeds need for germination (water, oxygen and a suitable temperature)	B11.02			
name the parts of the male reproductive system, and describe their functions	B11.03			
name the parts of the female reproductive system, and describe their functions	B11.03			
explain the adaptive features of eggs and sperm, and compare them	B11.03			
describe what happens at fertilisation	B11.03			

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CONTINUED

I can	See topic . . .	Needs more work	Almost there	Confident to move on
describe the functions of testosterone and oestrogen at puberty	B11.03			
describe the changes that take place in the ovaries and uterus during the menstrual cycle	B11.03			
explain what is meant by a sexually transmitted infection (STI)	B11.04			
state that HIV is a pathogen that can cause AIDS	B11.04			
explain how HIV is transmitted, and how its transmission can be controlled.	B11.04			

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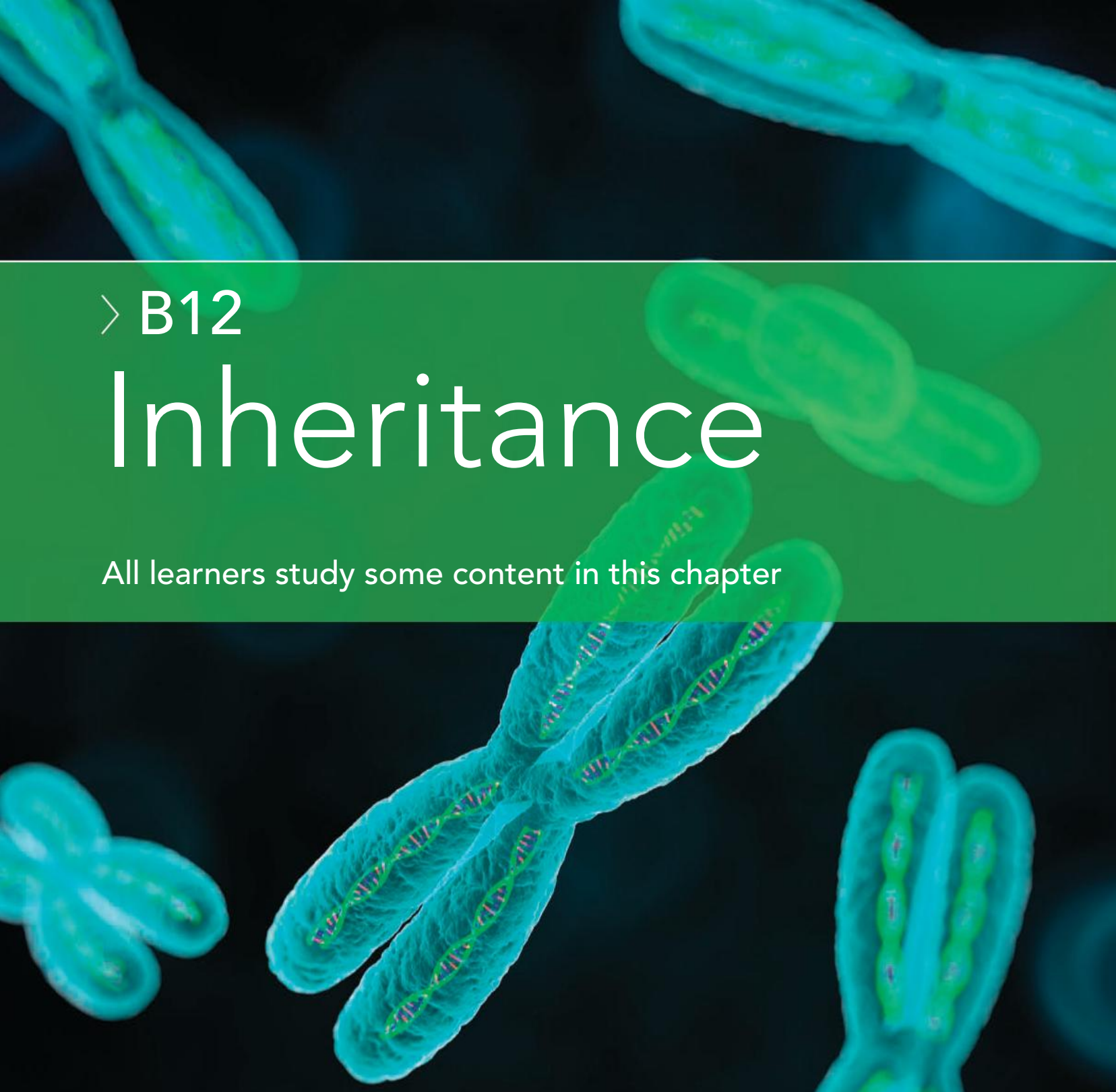

B12 Inheritance

All learners study some content in this chapter

IN THIS CHAPTER YOU WILL:

- learn about chromosomes and genes
- describe monohybrid inheritance
- use genetic diagrams to predict how characteristics are inherited
- find out about how and why cells divide by mitosis and meiosis.

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BEFORE YOU START

Earlier in your course, you have learnt about these structures or substances.

chromosome **DNA** **gamete** **zygote**

Choose one of these words, but do not tell anyone which one you have chosen.

Now ask a partner, or the rest of your group, to ask you questions to try to find out which word you are thinking of. You can only answer 'yes' or 'no'. The questions have to be about the meaning of the word, not the word itself. So, they cannot ask you if it begins with the letter c, for example.

SCIENCE IN CONTEXT B12.01

Breeding chinchillas

Chinchillas are small rodents, with very soft and thick fur. In the wild, they live in the Andes mountains in South America. They make good pets.

Imagine that a breeder wants to produce some unusual types of chinchilla. These can be worth more when the breeder sells them.

All the chinchillas that the breeder has are the normal, pale grey colour. But the breeder has a customer who wants to buy some chinchillas with charcoal (very dark grey) coats.

The breeder buys a male chinchilla with charcoal fur. He breeds this with one of his grey females. To his disappointment, all the offspring are pale grey (Figure B12.01).

The breeder reads up about the genetics of chinchilla fur colour. He learns that, although all of the offspring from his grey and charcoal chinchilla parents are grey, in fact they are carrying a 'hidden' gene for charcoal fur. To get more charcoal chinchillas, he needs to breed these offspring with their father or another charcoal chinchilla. He tries this and is successful: half of the offspring of this cross have grey fur, and half have charcoal fur.

Discussion questions

1 What do you think determines the coat colour of a chinchilla?

2 Do you think that all the features of a chinchilla are determined in this way?

Figure B12.01: A cross between a normal, grey chinchilla and a charcoal chinchilla is likely to produce grey offspring.

B12.01 Chromosomes and genes

The nucleus of every cell contains a number of long threads called chromosomes. Most of the time, the chromosomes are too thin to be seen except with an electron microscope. But when a cell is dividing, they become shorter and fatter so they can be seen with a light microscope. Figure B12.02 shows human chromosomes seen with a powerful electron microscope.

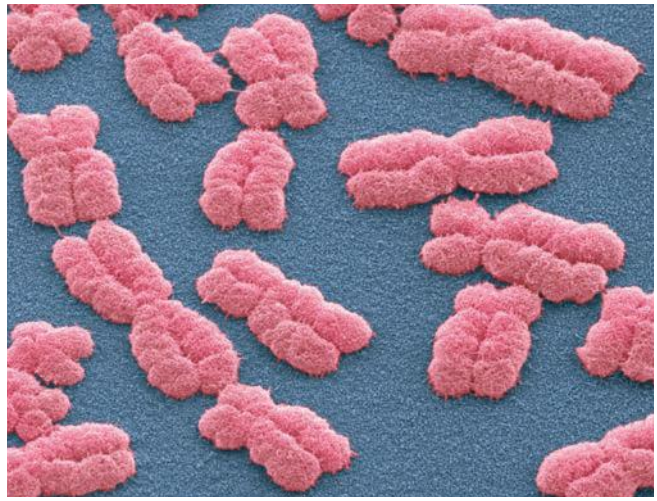

Figure B12.02: A scanning electron micrograph of human chromosomes, just before a cell divides. Each chromosome is made of two identical, thick threads joined together. These will split apart so that each cell gets a thread, when the cell divides.

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Each chromosome in a cell contains one very long molecule of DNA. The DNA molecule carries a code that instructs the cell about which kinds of proteins it should make. Each chromosome carries instructions for making many different proteins. A part of a DNA molecule with the instructions for making one kind of protein is called a **gene**.

The genes on your chromosomes determine all sorts of things about you. For example, they control what colour your eyes or hair are, whether you have a turned-up nose or a straight one, and whether or not you have a genetic disease such as cystic fibrosis. You inherited these genes from your parents.

Most genes come in more than one form or variety. The different forms of a gene are called **alleles**. For example, the gene coding for a protein that determines the colour of a chinchilla's fur might have alleles for charcoal (very dark grey) or pale grey fur.

Each species of organism has its own number and variety of genes. This is what makes their body chemistry, their appearance and their behaviour different from those of other species. Humans have many chromosomes and tens of thousands of genes. We each have 46 chromosomes inside each of our cells, all with many genes on them. Every cell in your body has an exact copy of all your genes.

All humans have the genes for the same characteristics, but we all differ in the alleles of those genes that we have. No one in the world has exactly the same combination of alleles that you have – unless you have an identical twin.

KEY WORDS

gene: a length of DNA that codes for one protein.

allele: alternative form of a gene.

Questions

B12.01 In which part of a cell is DNA found?

B12.02 Arrange these in order of size, smallest first:

cell **nucleus** **DNA molecule** **chromosome** **gene**

B12.03 Explain why your appearance is not the same as the appearance of anyone else in the world.

Chromosomes in haploid and diploid cells

We have seen that humans have 46 chromosomes in each cell. These 46 chromosomes are two sets of 23. One of these sets came from your mother, and the other set from your father.

You began your life as a single cell – a zygote – formed by the fusion of an egg cell and a sperm cell. The nuclei of each of these gametes contained a single complete set of 23 chromosomes. When they fused together, they produced a zygote with 46 chromosomes.

A cell with a single set of chromosomes, such as a gamete, is said to be haploid. The nucleus of the zygote that was formed when the egg cell and sperm cell fused together was diploid. The zygote was a diploid cell.

Figures B12.03 and B12.04 show the chromosomes in a cell of a woman and of a man, respectively. In each picture, the chromosomes have been arranged in order, largest first. They have also been arranged in pairs, with similar chromosomes from the two sets placed side by side. In each pair, one is from the person's mother and the other from their father. The two chromosomes of a pair are called homologous chromosomes.

ACTIVITY B12.01

Looking at chromosomes

Work with a partner.

First look carefully at the images in Figures B12.02, B12.03 and B12.04, and think about these questions on your own:

- What similarities and differences can you see in the images of the chromosomes in Figure B12.02, compared with the images in Figures B12.03 and B12.04? (The colour has been added artificially to the photographs, so this is not a significant difference between them.)
- In Figures B12.03 and B12.04, how do you think the numbers written underneath each pair of chromosomes have been decided on?
- What differences can you see between Figures B12.03 and B12.04?

Now turn to your partner and discuss your answers together.

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CONTINUED

Figure B12.03: Chromosomes of a woman, arranged in order. The photograph was taken using a light microscope.

Figure B12.04: Chromosomes of a man, arranged in order.

B12.02 Cell division

Mitosis

Think again about those two gametes fusing together in the very first moments of your life. Soon after the zygote was formed, it began to divide over and over again, producing a ball of cells that eventually grew into you. Each time a cell divided, the two new cells were provided with a perfect copy of the two sets of chromosomes in the original zygote. The new cells produced were all genetically identical.

This type of cell division, which produces genetically identical cells, is called mitosis. Mitosis is the way in which any plant or animal cell divides when an organism is growing or repairing a damaged part of its body. Mitosis produces new cells to make the body grow larger, or to replace damaged cells. For example, if you cut yourself, new skin cells will be made by mitosis to help to heal the wound.

Mitosis is also used in asexual reproduction. You have seen, for example, how a potato plant can reproduce by growing stem tubers which eventually produce new plants (Chapter B11). All the cells in the new tubers are produced by mitosis, so they are all genetically identical.

Just before mitosis takes place, each of the chromosomes in the parent cell is copied. This must happen so that there are enough chromosomes to be shared out into the new cells. For example, in a human, each cell needs to get 46 chromosomes of its own. Each copy remains attached to the original one, so each chromosome is made up of two identical threads joined together (Figures B12.02 and B12.05). The two identical threads are called chromatids, and the point where they are held together is called the centromere.

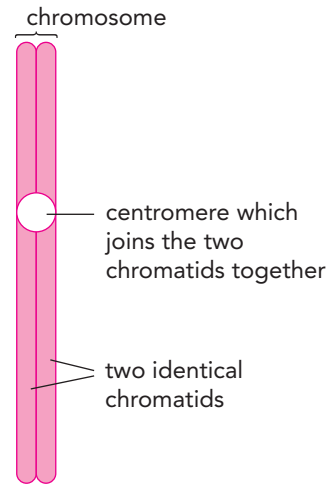

Figure B12.05: A chromosome just before cell division.

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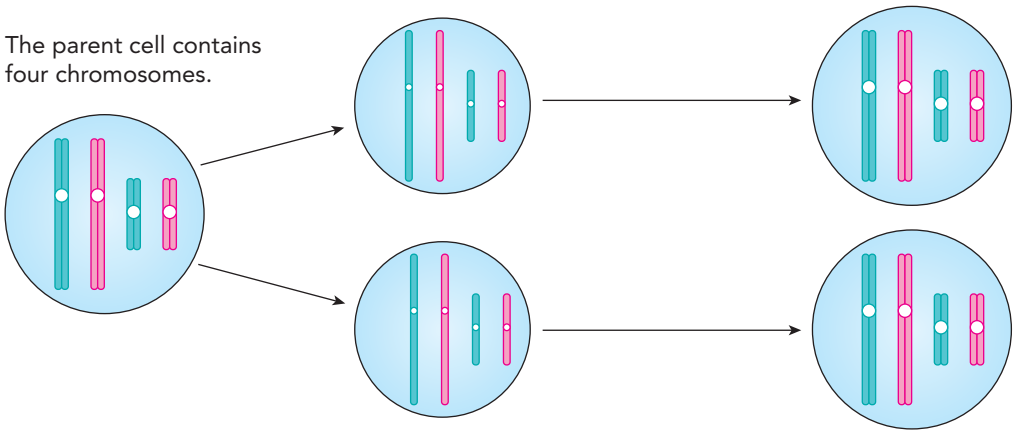

Figure B12.06: Chromosomes during the life of a cell dividing by mitosis.

On the left of Figure B12.06, you can see a diagram of a cell with four chromosomes. There are two sets of two chromosomes: the blue ones belong to one set, and the pink ones belong to the other set. The rest of the diagram shows what happens when this cell divides by mitosis.

At the end of mitosis, two new cells have been formed from one parent cell. The new cells are sometimes called daughter cells. Each daughter cell has one copy of each of the four chromosomes. As the new cells grow, they make new copies of each chromosome, ready to divide again.

Strictly speaking, we should think of mitosis as being a division of the *nucleus* of a cell, not of the cell itself.

This is because sometimes a nucleus divides to form two nuclei, which both stay inside the same cell. This happens, for example, when pollen grains develop. But normally the whole cell divides, not just the nucleus. So, we end up with new cells each with a nucleus containing perfect copies of the chromosomes that were present in the original cell.

Questions

B12.04 A cell that contains 32 chromosomes divides by mitosis. How many chromosomes are there in each of the two daughter cells produced?

B12.05 Explain, in your own words, why it is important that the two chromatids in a chromosome each contain exactly the same genetic information.

B12.06 Before a human cell divides by mitosis, the 46 chromosomes each form two genetically identical chromatids. Suggest why it is important that these two chromatids remain held together until the cell is ready to split into two.

Meiosis

In Chapter B11, we saw that sexual reproduction always involves gametes. Gametes have only half the number of chromosomes of a normal body cell. They are haploid cells. Gametes have one set of chromosomes instead of two sets. This is so that when they fuse together, the zygote formed has two sets.

Human gametes are formed by the division of cells in the ovaries and testes. The cells divide by a special type of cell division called meiosis. Meiosis shares out the chromosomes so that each new cell gets just one chromosome of each homologous pair. The new cells, therefore, each have a single set of chromosomes. The diploid parent cell produces haploid daughter cells.

Meiosis is said to be a **reduction division**. This means that the number of chromosomes is halved – or reduced – as a result of meiosis. In humans, for example, a diploid cell with 46 chromosomes divides by meiosis to form haploid daughter cells each with 23 chromosomes.

KEY WORDS

reduction division: a term used to describe what happens in meiosis, where the number of chromosomes is halved (reduced).

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You do not need to know any details of what happens during meiosis. However, Figure B12.07 may help you understand how it works. This diagram shows how a diploid cell with four chromosomes can divide by meiosis to produce four haploid cells, each with two chromosomes. The cell actually divides twice. The first division separates the chromosomes from their homologous partners (this is the reduction division). Then the second division splits the chromatids in each chromosome apart.

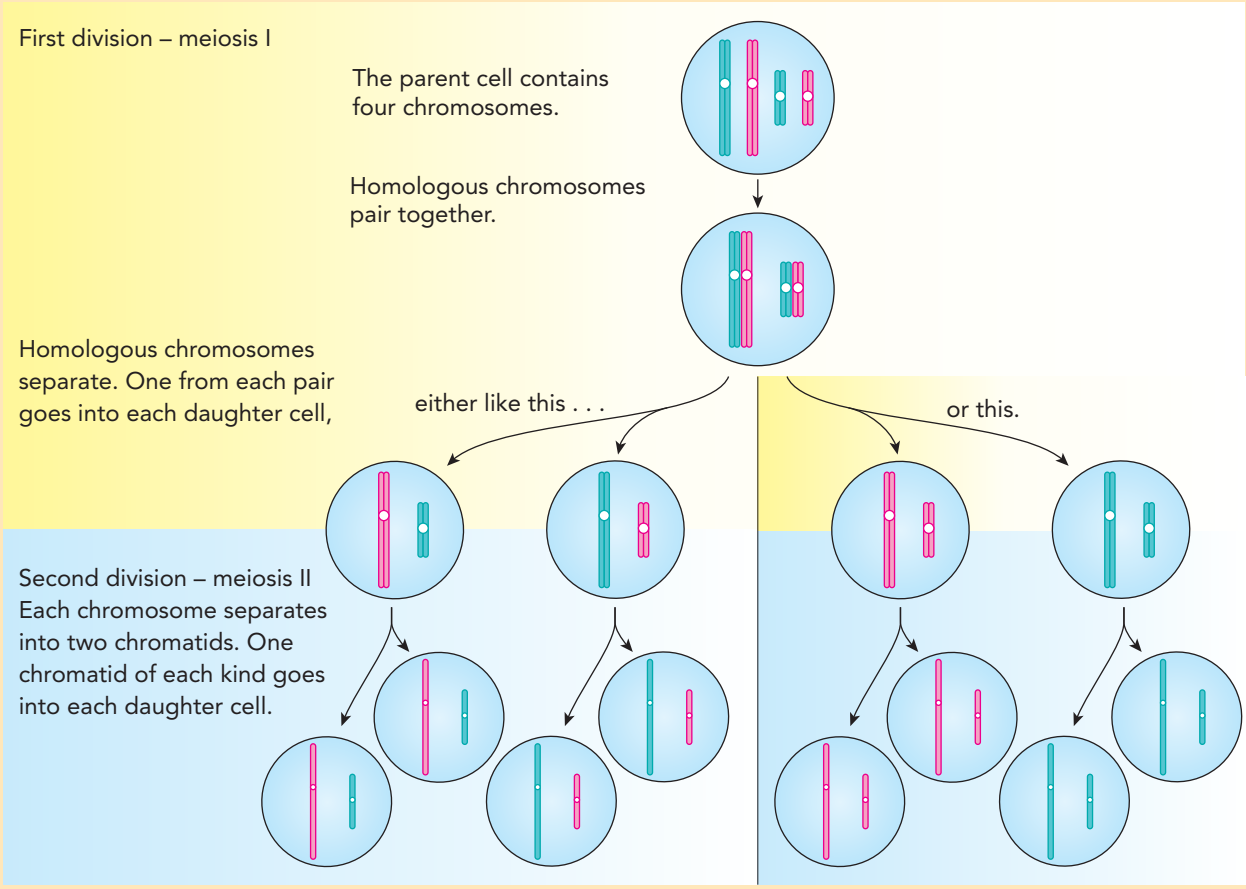

Figure B12.07: How meiosis produces haploid cells from a diploid cell.

You may remember that one of each pair of homologous chromosomes came from the person's mother, and one from their father. During meiosis, the new cells get a mixture of these. So, a sperm cell could contain a chromosome 1 from the man's father and a chromosome 2 from his mother, and so on. There are all sorts of different possible combinations. This is one of the reasons why gametes are genetically different from the parent cell. Meiosis produces genetic variation in the gametes and in the offspring.

Questions

B12.07 Explain why meiosis is called a 'reduction division'.

B12.08 A cell has a diploid number of 28. How many chromosomes will there be in each of the daughter cells produced by meiosis?

B12.09 Explain why it is important that human gametes are produced by meiosis, and not by mitosis.

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B12.03 Monohybrid inheritance

We have seen that chromosomes each contain many genes. We think there are about 20 000 human genes, carried on our two sets of 23 chromosomes.

Because you have two complete sets of chromosomes in each of your cells, you have two complete sets of genes. Each chromosome in a homologous pair contains genes for the same characteristic in the same positions (Figure B12.08).

Let us look at one kind of gene to see how it behaves, and how it is inherited.

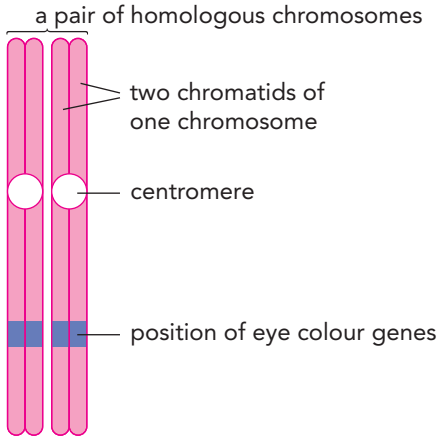

Figure B12.08: Homologous chromosomes have genes for the same characteristic in the same position. Here, the position of a gene that codes for eye colour is shown. There would be hundreds of other genes on each chromosome.

Genes and alleles

In chinchillas, genes determine the colour of the fur. The genes are sets of coded instructions for producing the proteins that cause different fur colours. We have seen that there are different forms of the fur colour gene, and that these different forms are called alleles.

We can refer to these alleles using letters as symbols. For example, we can call the allele that gives grey fur **G**, and the allele that gives charcoal fur **g**.

Because there are *two* of every kind of chromosome in each cell in a chinchilla's body, there are also *two* genes giving instructions about which kind of fur colour protein to make. This means that there are *three* possible combinations of alleles. A chinchilla might have two **G** alleles, **GG**. It might have one of each, **Gg**. Or it might have two **g** alleles, **gg** (Figure B12.09).

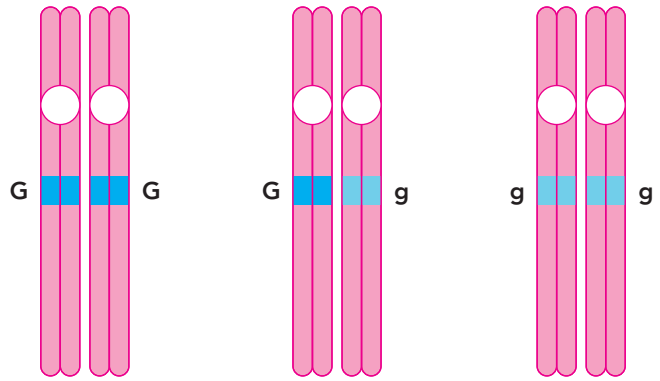

Figure B12.09: Genotypes for the fur colour gene in chinchillas.

If the two alleles for this gene are the same – that is, **GG** or **gg** – the chinchilla is said to be **homozygous**. If the two alleles are different – that is, **Gg** – then it is **heterozygous**.

Genotype and phenotype

The genes that a chinchilla has are its **genotype**. Its genotype for fur colour could be **GG**, **Gg** or **gg**.

If its genotype is **GG**, then it has light grey fur. If its genotype is **gg** it has charcoal fur. If its genotype is **Gg** it has light grey fur.

The features the chinchilla has are called its **phenotype**. The phenotype of an organism can include what it looks like – for example, the colour of its fur – as well as things which we cannot actually see, such as what kind of protein it has in its cell membranes.

KEY WORDS

homozygous: having two identical alleles of a particular gene (e.g. **GG** or **gg**).

heterozygous: having two different alleles of a particular gene (e.g. **Gg**).

genotype: the genetic makeup of an organism in terms of the alleles present (e.g. **GG**).

phenotype: the observable features of an organism.

You can see that, in this example, the chinchilla's phenotype for fur colour depends entirely on its genotype. This is not always true. Sometimes, other things, such as what it eats, can affect its phenotype. However, for the moment, we will only consider the effect that genotype has on phenotype, and not worry about effects that the environment might have.

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Dominant and recessive alleles

We have seen that there are three different possible genotypes for chinchilla fur colour, but only two phenotypes. We can summarise this as follows:

Genotype	Phenotype
GG	grey
Gg	grey
gg	charcoal

Table B12.01: Chinchilla fur colour.

This happens because the allele **G** is dominant to the allele **g**. A **dominant allele** has just as much effect on phenotype when there is only one of it as when there are two of it. A chinchilla that is homozygous for a dominant allele has the same phenotype as a chinchilla that is heterozygous. A heterozygous chinchilla is said to be a carrier of the charcoal colour because it has the allele for it but does not have charcoal fur.

The allele **g** is recessive. A **recessive allele** only affects the phenotype when there is no dominant allele present. Only chinchillas with the genotype **gg** – homozygous recessive – have charcoal fur.

KEY WORDS

dominant allele: an allele that is expressed if it is present (e.g. **G**).

recessive allele: an allele that is only expressed when there is no dominant allele of the gene present (e.g. **g**).

Questions

B12.10 In a species of animal, the allele for brown eyes is dominant and the allele for green eyes is recessive.

- **a** Write down suitable symbols for these two alleles.
- **b** Using your symbols, write the three possible genotypes, and the phenotypes that are produced by each genotype.
- **c** Which of the genotypes you have written are homozygous, and which are heterozygous?

B12.11 In a species of plant, there are two alleles of the gene that determines leaf shape. One allele produces round leaves, and the other produces oval leaves. Heterozygous plants have round leaves.

Which allele is dominant? Explain how you can tell.

B12.12 When we choose symbols for alleles, it is not a good idea to choose letters such as S or C. Letters like A or B are better choices. Can you suggest why?

Alleles in gametes

An understanding of genes and alleles can be used to study and predict how characteristics are passed on from one generation to the next. This area of study is called genetics. Geneticists study **inheritance**. Inheritance is the transmission of genetic information from generation to generation.

KEY WORD

inheritance: the transmission of genetic information from generation to generation.

The genetic information is transferred in gametes. Each gamete has only one of each kind of chromosome instead of two, as in the body cells. So, for example, human egg and sperm cells have 23 chromosomes, not 46 as in other cells. These cells, therefore, only carry *one* of each pair of alleles of all the genes.

Imagine a male chinchilla that has the genotype **Gg**. He is a carrier for charcoal fur. In his testes, sperm are made by meiosis. Each sperm cell gets either a **G** allele or a **g** allele. Half of his sperm cells have the genotype **G** and half have the genotype **g** (Figure B12.10).

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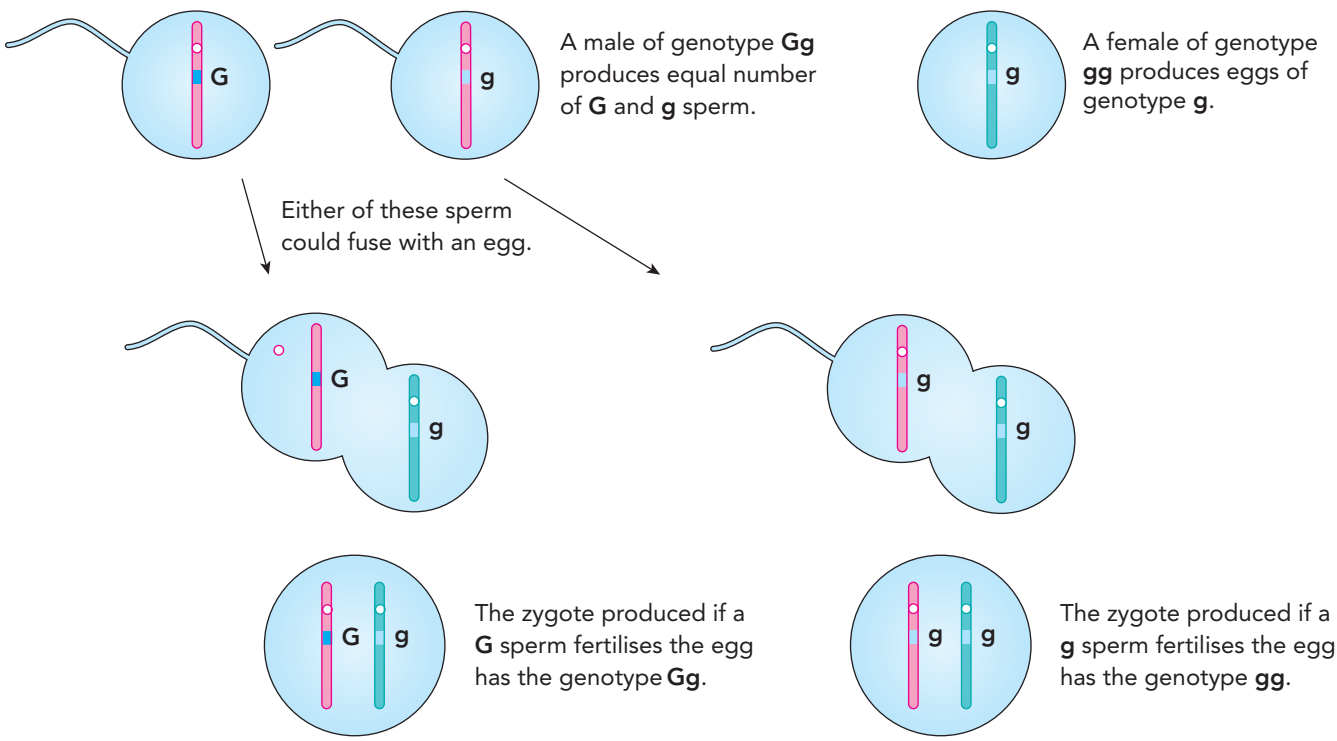

Figure B12.10: Fertilisation between a heterozygous light grey male chinchilla and a female chinchilla with charcoal fur.

Genes and fertilisation

If this heterozygous chinchilla is crossed with a female with charcoal fur (genotype **gg**), will their offspring have charcoal fur?

The eggs that are made in the female's ovaries are also made by meiosis. She can only make one kind of egg. All of her eggs will carry a **g** allele.

When the two chinchillas mate, hundreds of thousands of sperm will begin a journey towards the egg. About half of these sperm will carry a **G** allele, and half will carry a **g** allele. If there is an egg in the female's oviduct, it will probably be fertilised. There is an equal chance of either kind of sperm getting there first.

If a sperm carrying a **G** allele wins the race, then the zygote will have a **G** allele from its father and a **g** allele from its mother. Its genotype will be **Gg**. When the baby chinchilla is born, it will have the genotype **Gg**.

But if a sperm carrying a **g** allele manages to fertilise the egg, then the baby will have the genotype **gg**, like its mother (Figure B12.10).

Questions

B12.13 Write down the genotypes of the different kinds of gametes that can be produced by organisms with each of these genotypes:

- **a** **TT**
- **b** **Tt**
- **c** **tt**

B12.14 Two organisms with the genotype **TT** breed together. Use your answer to B12.13a to write down the only possible genotype of their offspring.

B12.15 An organism with genotype **TT** breeds with an organism with the genotype **tt**. Use your answers to B12.13a and B12.13c to write down the only possible genotype of their offspring.

B12.16 An organism with genotype **TT** breeds with an organism with the genotype **Tt**. Use your answers to B12.13a and B12.13b to write down the two possible genotypes of their offspring.

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Genetic diagrams

There is a standard way of writing out all this information about how the alleles from two parents can be passed on to their offspring. It is called a **genetic diagram**.

First, write down the phenotypes and genotypes of the parents. Next, write down the different types of gametes they can make, like this:

Parents' phenotypes	grey	charcoal
Parents' genotypes	**Gg**	**gg**
Gametes	(G) or (g)	(g)

Table B12.02: The genotypes of a grey and a charcoal chinchilla and the gametes they produce.

Notice that the genotypes of the gametes have circles around them. It is a really good idea to do this, as it makes the gametes stand out and helps you keep track of all the symbols in your genetic diagram.

The next step is to write down what might happen during fertilisation. Either kind of sperm might fuse with an egg:

Offspring genotypes and phenotypes

Sperm \ Eggs	(g)
(G)	**Gg** grey
(g)	**gg** charcoal

To finish your summary of the genetic cross, write out in words what you would expect the offspring from this cross to be. In this case, we would expect approximately half of the offspring to be heterozygous with grey fur, and half to be homozygous with charcoal fur. Another way of putting this is to say that the expected ratio of grey fur to charcoal fur would be 1 : 1.

It is really important to understand that this genetic diagram does *not* mean that the chinchillas will have two offspring, one grey and one charcoal. What it means is that there are equal chances of having a grey offspring or a charcoal offspring.

This cross, and all the others in this chapter, are examples of **monohybrid crosses**. This means that we are looking at the inheritance of only one ('mono') gene.

Another genetic cross

Here is a genetic diagram that we can use to predict the offspring that might be born if two heterozygous chinchillas mate with each other:

Parents' phenotypes	grey	grey
Parents' genotypes	**Gg**	**Gg**
Gametes	(G) or (g)	(G) or (g)

Table B12.03: The genotypes of grey chinchillas and the gametes they produce.

Offspring genotypes and phenotypes

Sperm \ Eggs	(G)	(g)
(G)	**GG** grey	**Gg** grey
(g)	**Gg** grey	**gg** charcoal

This looks more complicated than the first genetic diagram because this time both the parents can produce two different types of gametes. The set of boxes that show all the possible results of these gametes fusing together is called a **Punnett square**. It is a neat way of working out and showing the possible combinations of alleles that might occur. The boxes in the Punnett square are also the best place to write down the phenotypes that each of the genotypes produce.

We can use the entries in the Punnett square to work out the expected proportions of the different kinds of offspring that might be produced. We would expect about one-quarter of the offspring to have charcoal fur, and three-quarters to have grey fur.

KEY WORDS

genetic diagram: a standard way of showing all the steps in making predictions about the probable genotypes and phenotypes of the offspring from two parents.

monohybrid cross: a cross where we consider the inheritance of only one gene.

Punnett square: the part of a genetic diagram that shows the predicted genotypes and phenotypes that can result from the random fusion of the male and female gametes.

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Probabilities in genetics

In the last example, there were four possible offspring genotypes at the end of the cross. This does not mean that the two chinchillas will have four offspring. It simply means that each time they have offspring, these are the *possible* genotypes that they might have, in those *probable* proportions.

The Punnett square tells us that, for any one offspring, there is a 1 in 4 chance that its genotype will be **GG**, and a 1 in 4 chance that its genotype will be **gg**. There is a 2 in 4, or 1 in 2, chance that its genotype will be **Gg**.

However, as you know, probabilities do not always work out. If you toss a coin up four times you might expect it to turn up heads twice and tails twice. But does it always do this? Try it and see.

With small numbers like this, probabilities do not always match reality. However, if you have the patience to toss your coin up a few thousand times, you will almost certainly find that you get nearly equal numbers of heads and tails.

The same thing applies in genetics. The offspring genotypes that you work out are only probabilities. With small numbers, they are unlikely to be exactly what we predict. With very large numbers of offspring from one cross, they are more likely to be accurate.

So, for example, we might use a genetic diagram to predict that one-quarter of the kittens born to a pair of cats would be expected to have black fur, one-quarter to have ginger fur and the remaining half to have grey fur. But the cats might actually have seven kittens (Figure B12.11) and the proportions might not work out exactly as we predicted. This is because which sperm fuse with which eggs is all due to chance.

Figure B12.11: Genetic diagrams do not give us any information at all about how many offspring will be produced. The probable phenotypes that they predict are only probabilities, not certainties.

ACTIVITY B12.02

Breeding beads

Work in a group of two or three for this activity.

You will need:

- two containers
- approx. 150 beads of one colour, and 150 of another colour.

Each container represents a parent. The beads represent the alleles in the gametes they make. The colour of a bead represents the genotype of the gamete. For example, a red bead might represent a gamete with genotype **A**, for 'long tail'. A yellow bead might represent a gamete with the genotype **a**, for 'short tail'.

Method

1. Put 100 red beads into the first container. These represent the gametes of an animal that is homozygous for the long tail allele, **AA**.
2. Put 50 red beads and 50 yellow beads into the second container. These represent the gametes of a heterozygous animal with the genotype **Aa**.
3. Close your eyes, and pick out one bead from the first container, and one from the second. Write down the genotype of the 'offspring' they produce. Put the two beads back.
4. Repeat step 3 100 times, recording the genotype of the offspring each time.
5. Count how many of each genotype there are in the offspring. Write down the ratios of the different genotypes and phenotypes of the offspring that were produced.
6. Now try a different cross – for example, **Aa** crossed with **Aa**.

Question

How well do the ratios of the different phenotypes and genotypes of the 'offspring' match the ratios predicted by a genetic diagram? If they are not exactly the same, suggest why this is.

Self assessment

A lot of patience is needed to complete this task. How well did you manage to concentrate?

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CONTINUED

Reflection

This is quite a time-consuming process for you, and it is easy to get the beads muddled up. What did you do to help to keep focused, and to avoid mistakes?

Are there other activities that you regularly do in your biology work where you have to work hard to stay focused? What tactics do you use to help you?

Pedigree diagrams

A pedigree diagram is a way of showing the phenotypes (and sometimes the genotypes, too) of the family members in several generations. All the individuals in one generation are shown in the same row. Males are shown with a square symbol, and females with a circle. Parents are connected with a horizontal line between them, and a vertical line leads down to their offspring.

Guinea pigs can have smooth hair or curlier hair that forms rosettes (Figure B12.12). Figure B12.13 is a pedigree diagram showing the phenotype for hair in three generations of guinea pigs.

Figure B12.12: The guinea pig on the left has a smooth coat, while the one on the right has rosettes.

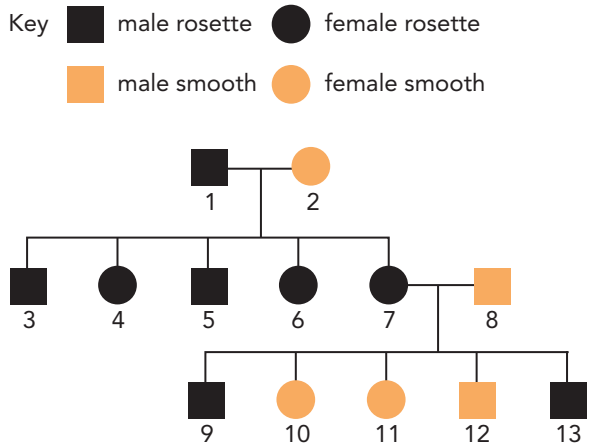

Figure B12.13: Pedigree diagram showing phenotype for smooth or rosette hair in three generations of guinea pigs.

What can we work out from this pedigree diagram? In the first row, there is a male rosette guinea pig that has mated with a female smooth guinea pig. They have had five offspring, all with rosette hair. This strongly suggests that the allele for rosette hair is dominant. We can, therefore, try using **R** to represent the rosette hair allele, and **r** for the smooth hair allele.

If we are correct, then all of the smooth-haired guinea pigs must have the genotype **rr**. So, we now know the genotypes of guinea pigs 2, 8, 10, 11 and 12 must all be **rr**.

But what about the others? Look at guinea pig 1. He has rosette hair, so he could be **RR** or **Rr**. If he is **Rr**, then he would be able to make some sperm with the **R** allele, and some with the **r** allele. If so, then we would expect at least some of his offspring to get an **r** allele from him, as well as from the female. This would make the offspring smooth. But none of them are smooth, so it seems likely that he is **RR**, not **Rr**. But we cannot be sure – perhaps it is just chance that no **r** sperm met up with an **r** egg.

Now look at guinea pig 7. She has rosette hair, so again she could be **RR** or **Rr**. She has mated with a smooth male, and they have had five offspring. Three of these have smooth hair, so they must be **rr**. And this means that they have received an **r** allele from their mother, as well as from their father. So, guinea pig 7 must have the genotype **Rr**.

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Questions

B12.17 Fruit flies can have normal wings or wings that are so small that they are useless. These are called vestigial wings. The allele for normal wings, **N**, is dominant, and the allele for vestigial wings, **n**, is recessive.

a Write down the three possible genotypes and their phenotypes.

b Construct a complete genetic diagram to show the offspring that are produced when a heterozygous fly mates with a fly that is homozygous for the normal wing allele.

B12.18 In a species of animal, the allele for red hair is recessive to the allele for brown hair. Two animals have five offspring, three with red hair and two with brown hair. Use a genetic diagram to explain how this can happen.

REFLECTION

In a situation where time is limited, such as in an examination, it is tempting to take short cuts with your answers to genetic questions. For example, you might not bother to write a list of genotypes and phenotypes before you start, or you may decide to skip the Gametes row in the genetic diagram.

Do you think there are circumstances where it is justifiable to take these short cuts? Or is it better always to work thoroughly through each step?

PROJECT B12.01 STEM CELLS IN MEDICINE

Stem cells were first discovered in the 1970s. Today, many different teams of scientists all over the world are carrying out research to try to find ways in which we might be able to use stem cells to improve people's health.

Work in a group of three or four for this project. You are going to write a short, scripted news piece on one aspect of the use of stem cells. You can include still pictures or video content if you wish. You may be able to present your completed news piece to the rest of the class.

Here are some topics that you could research. Choose one of them – or feel free to think of a different one of your own. Try to make sure that you are not researching the same topic as any other group in your class.

- What is a stem cell? Why are stem cells important in an organism?
- What are the differences between the stem cells in an embryo, and the stem cells in an adult person? How does this affect the way that these stem cells might be used in medicine?
- Most countries regulate the kind of research that scientists can do on stem cells. Why do they do this, and what kind of regulations do they impose? Do you agree with the regulations?
- Are stem cells being used today to treat any diseases in humans? If so, how are they being used, and how is the treatment being regulated?
- How do scientists think that stem cells might be used in the future?

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SUMMARY

Chromosomes are long strands of DNA, which contain genetic information in the form of genes. Each gene codes for the production of a particular kind of protein.
Most genes come in different forms, called alleles.
A haploid cell has one set of chromosomes, while a diploid cell has two sets. In humans, haploid cells contain 23 chromosomes and diploid cells contain 46 chromosomes, that is 23 pairs. The two similar chromosomes from the two sets are called homologous chromosomes.
Mitosis is a division of the nucleus of a cell, in which the two new nuclei contain exactly the same number and types of chromosomes as the parent nucleus. Usually, the whole cell divides after the nucleus has divided, producing two genetically identical daughter cells.
Mitosis is used in growth, repair of damaged tissues, replacement of cells and asexual reproduction.
Meiosis is a reduction division, in which a diploid cell divides to produce haploid cells. These are genetically different from their parent cell and from each other. Meiosis is used to produce gametes.
Inheritance is the transmission of genetic information from generation to generation.
We can use letters to represent the alleles of a gene. An allele that has an effect even when a different allele is present is said to be dominant and is represented with a capital letter. An allele that only has an effect when no other allele is present is said to be recessive and is represented by a small letter.
The alleles of a gene that an organism has are its genotype, and the features produced by those alleles are its phenotype.
There are two copies of each gene in every body cell. If both copies are the same allele, the organism is homozygous. If there are two different alleles, the organism is heterozygous. Homozygous organisms are pure-breeding, but heterozygous organisms are not.
We can use genetic diagrams to show how alleles are passed from one generation to the next, which is called inheritance. If we consider the alleles of only one gene, then this is a monohybrid cross.
Each gamete contains only one allele of a gene. Any male gamete can fuse with any female gamete, and we can show the resulting genotypes and phenotypes of the offspring using a Punnett square.

PRACTICE QUESTIONS

1 **Identify** which of A–D shows the sex chromosomes found in the gametes of a man and a woman.

	Gametes from a man	Gametes from a woman
A	X only	X or Y
B	X or Y	X only
C	Y only	X or Y
D	X or Y	Y only

[1]

2 Identify the number of pairs of chromosomes in a diploid human cell.

A 2 **B** 23

C 46 **D** 92 **[1]**

COMMAND WORD

identify: name/select/recognise.

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CONTINUED

3 The list below shows seven inheritance key terms.

allele **dominant** **heterozygous** **phenotype** **monohybrid** **genotype** **recessive**

Use the key terms to answer the following questions.

a **Identify** the term used to describe an organism that has two different alleles of the same gene. **[1]**

b Identify the term used to describe the observable features of an organism. **[1]**

c Identify the term used to describe an allele that only has an effect when a different allele is not present. **[1]**

d Identify the term used to describe one of several different forms of a gene. **[1]**

[Total: 4]

4 The leaves of tomato plants can have leaves with smooth or indented edges. The allele for indented edges, **E**, is dominant, and the allele for smooth edges, **e**, is recessive.

a **Give** the genotypes of:

i a homozygous smooth plant **[1]**

ii a homozygous indented plant. **[1]**

b A homozygous smooth plant was crossed with a homozygous indented plant. All of the offspring had the genotype **Ee**.

Several of these offspring were crossed together. There were 302 plants with indented leaves and 99 with smooth leaves. Construct a complete genetic diagram to **explain** this result. **[3]**

[Total: 7]

COMMAND WORD

Identify: name/select/recognise.

COMMAND WORDS

give: produce an answer from a given source or recall/memory.

explain: set out purposes or reasons/make the relationships between things clear/say why and/or how and support with relevant evidence.

SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
explain what is meant by the terms *chromosome*, *DNA*, *gene* and *allele*	B12.01			
describe the roles of mitosis in organisms	B12.02			
describe the role of meiosis in organisms	B12.02			
use appropriate symbols to represent the alleles of a gene, and explain the meanings of the terms *dominant*, *recessive*, *homozygous* and *heterozygous*	B12.03			
use the terms *phenotype* and *genotype* and relate the phenotype of an organism to its genotype	B12.03			
construct genetic diagrams – including Punnett squares – to predict the genotypes and phenotypes in a monohybrid cross.	B12.03			

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B13

Variation and selection

Only learners entered for Co-ordinated Core and Co-ordinated Supplement study this content

IN THIS CHAPTER YOU WILL:

- find out about discontinuous and continuous variation, and what causes them
- learn about mutations
- identify and describe adaptive features in different species
- think about how selection can cause changes in the features of a species or population
- learn why antibiotics are used and why they are an example of a drug.

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BEFORE YOU START

Think about the answers to these questions.

1 What is the difference between a gene and an allele?
2 What are genes and alleles made of?
3 How are alleles passed from one generation to the next?

SCIENCE IN CONTEXT B13.01

Confusing butterflies

The two butterflies in Figure B13.01 look very different. Most people would assume they belong to two different species. But that is not the case. Both butterflies belong to the species *Papilio polytes*, the common mormon butterfly.

This species of butterfly is found in many different countries in Asia. The males always look the same – like the top picture. Some of the females look just like the male. But some – such as the one shown in the bottom picture – have very different wing shapes and colours.

The butterfly in the bottom picture, with the pink colour on its wings, is called the *stichius* form of the common mormon. This form is found only where another butterfly that looks very similar, the common rose swallowtail, is found. The common rose swallowtail is poisonous, so predators quickly learn to avoid catching it. The common mormon is not poisonous. By pretending to be a common rose swallowtail, the female butterflies are much less likely to be eaten.

This pretence is called mimicry. It only works if there are large numbers of the genuinely poisonous butterfly, and much smaller numbers of the non-poisonous one – otherwise, predators would not learn to avoid them.

Discussion questions

1 Why do you think that the *stichius* form of the butterfly is only found where the common rose swallowtail butterfly is found?
2 Can you think of any reasons why it might be more important for the female butterfly to avoid predation, than for the male?

Figure B13.01: Variation in shape and colour in the common mormon butterfly.

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B13.01 Variation

Look around your classroom. Everyone is different from everyone else. Some of the more obvious differences are in height or hair type. We also vary in blood groups, the shape of our ears, how good we are at sport, how sociable we are and many other ways. Differences between individuals belonging to the same species are called **variation**.

Continuous and discontinuous variation

There are two basic types of variation. One type is **discontinuous variation**. This results in a limited number of phenotypes between two extremes, e.g. tongue rolling. Blood groups are an example of discontinuous variation. Everyone fits into one of four definite categories. Each of us has group A, B, AB or O. There are no intermediate (in-between) categories.

Figure B13.02 is a graph showing discontinuous variation in blood groups. On the *x*-axis, because each blood group is a separate, distinct category, there is no continuous scale. The percentages of people in the **population** with each blood group are shown as bars with gaps between them. It would not be appropriate to use a line graph.

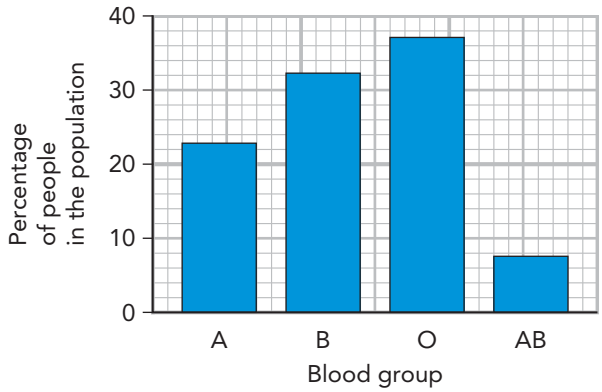

Figure B13.02: Percentages of people with the four blood groups in an Asian country. This is an example of discontinuous variation.

Another type of variation is **continuous variation**. Height in humans is an example of continuous variation (Figure B13.03). There are no definite height categories that a person must fit into. People vary in height, between the lowest and highest extremes. There is a complete range of phenotypes between these extremes.

Figure B13.04 shows continuous variation in height. We can show these data as a histogram (frequency diagram). Notice that the scale on the *x*-axis now goes up steadily, rather than having completely separate categories as in Figure B13.02.

The bars in a histogram touch each other, because the scale is continuous.

Figure B13.03: Human height shows continuous variation. What characteristic here shows discontinuous variation?

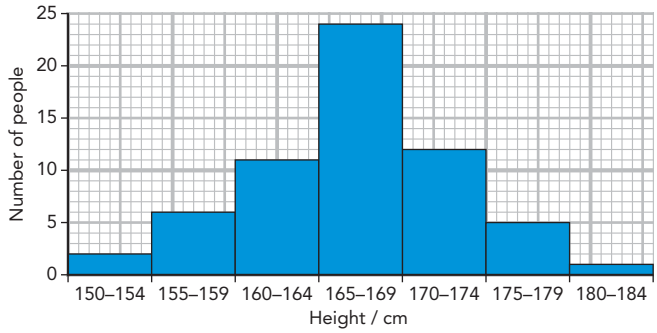

Figure B13.04: Histogram (frequency diagram) showing continuous variation in height.

We can also represent continuous variation as a line graph (Figure B13.05). Very often, we find that the data produce a bell-shaped curve. Most individuals come somewhere in the middle of the range, with smaller numbers at the extremes.

KEY WORDS

variation: differences between the individuals of the same species.

discontinuous variation: variation in which there are distinct categories of phenotype, with no intermediates.

population: a group of organisms of one species, living in the same area at the same time.

continuous variation: variation in which there is a continuous range of phenotypes between two extremes.

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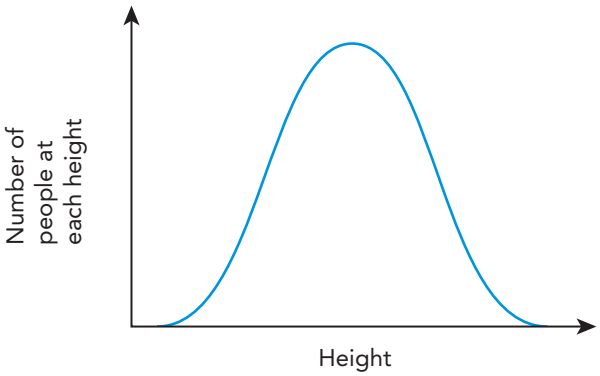

Figure B13.05: Line graph showing continuous variation in height.

Mutation causes genetic variation

Sometimes, a gene may suddenly change. This is called **mutation**. Mutation is how new alleles are formed. Mutations are the only source of brand-new characteristics that appear in a species. So, mutations are really the source of all genetic variation.

KEY WORD

mutation: a random change in a gene, which can produce new alleles; mutation involves a change in the base sequence in DNA.

EXPERIMENTAL SKILLS B13.01

Measuring continuous variation in humans

In this investigation, you will collect data about continuous variation in the people in your class. You will then practise recording these data in tables and graphs.

You will need:

- A ruler or tape measure.

Method

1 Measure the length of the third finger of the left hand of everyone in your class. (It is best if you can take measurements from at least 30 people, so if there are not that many in your class, perhaps you can also include measurements from another class.) Take the measurement from the knuckle to the finger tip, not including the nail.

CONTINUED: B13.01

2 Divide the finger lengths into suitable categories, and record the numbers in each category, like this.

Length / cm	Number of measurements
8.0–8.4	2
8.5–8.9	4

3 Construct a histogram to display your data. You can use Figure B13.04 for guidance.

Questions

1 The category, or class, which has the largest number of individuals in it is called the modal class. What is the modal class for finger length in your results?

2 The mean finger length is the total of all the finger lengths, divided by the number of people in your sample. What is the mean finger length of the sample?

3 Do you think that variation in finger length is affected by genes, the environment or both? Explain your answer.

Questions

B13.01 State whether each of these features shows continuous variation or discontinuous variation.

- **a** blood group in humans
- **b** foot length in humans
- **c** leaf length in a species of tree
- **d** presence of horns in cattle

B13.02 For each of the examples in **a** to **d** above, suggest whether the variation is caused by genes alone, or by both genes and environment.

B13.03 In peas, seeds can be either yellow or green. Plants grown from green seeds are pure-breeding, but plants grown from yellow seeds can produce some green seeds when they are bred together.

- **a** Is this an example of continuous variation or discontinuous variation? Explain your answer.
- **b** Explain how this variation is caused.

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B13.04 Figure B13.06 shows a maize cob. Each of the kernels (fruits) in the cob is a new individual.

Figure B13.06: A maize cob showing variation in kernel colour.

a Does colour in maize kernels show continuous variation or discontinuous variation? Explain your answer.

b Estimate the ratio of white : brown kernels in the maize cob.

c Suggest suitable symbols for the alleles that have produced these colours, and also suggest the genotypes of the parents that produced the offspring in this maize cob.

B13.02 Selection

Every organism has features that help it to survive in its environment. In this topic we will look at how the features of the organism can affect its chances of reproduction, and therefore the chances of its genes being passed on to the next generation.

Some features are very obvious. All fish, for example, have gills that allow them to obtain oxygen under water. Different species of fish have adaptations that help them to survive in different environments (Figure B13.07). For example, fish that live on sand in shallow water may have very flat, sand-coloured bodies, so that they are camouflaged from predators. Predatory fish that live in the open ocean have streamlined bodies for fast swimming, and teeth that they use to kill their prey.

Other features may not be so easy to spot. For example, the pygmy seahorse and the tuna might have different enzymes in their digestive systems so that they are efficient at digesting the nutrients in their different diets. The tuna might have more mitochondria in its muscle cells than the seahorse, to provide more energy through aerobic respiration, allowing it to swim faster.

Figure B13.07 a: The pygmy seahorse is adapted to be perfectly camouflaged among the sea fans where it lives. **b**: Tuna are fast-swimming predators, with streamlined bodies and strong swimming muscles.

So individuals within a population are not all the same: they show variation. Within a population of pygmy seahorses, perhaps some have slightly different colouration, so that some are slightly better camouflaged than others. Within a population of tuna, perhaps some individuals have more mitochondria than others, so they can release more energy and swim just a little bit faster than the rest of the population.

An animal or plant that is well adapted to its environment is much more likely to survive than one that is not. A pygmy seahorse that was bright blue instead of pink and white would not be camouflaged and would probably be killed and eaten by a predator long before it reached adulthood. Only well-adapted individuals have a good chance of living long enough to reproduce.

Variation is often caused by genes. Individuals whose alleles give them slightly better adaptive features are more likely to survive and reproduce than the other individuals in the population. So, their alleles are more likely to be passed on to the next generation.

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Over time, this results in more and more of the population having these alleles. They are better **adapted**. The better-adapted individuals survive and reproduce, while those that have alleles that do not provide quite as good adaptive features die. We say that the better-adapted individuals – those that have alleles that give them slightly better adaptive features – are selected.

This process is called **natural selection**. It is happening all the time, in all the populations of all the different species of organism in the world.

KEY WORDS

adaptation (adapted): the process, resulting from natural selection, by which populations become more suited to their environment over many generations.

natural selection: a process in which individuals with advantageous features are more likely to survive, reproduce and pass on their alleles to the next generation.

We can summarise natural selection in four points.

1 Variation: There is variation within a population of organisms. Some of these variations are caused by having different alleles of genes. Some of the variation affects the adaptive features of the organisms.

2 Overproduction: Within a wild population, many more offspring are produced than will survive to become adults and reproduce. For example, only about half of all the zebra foals that are born will survive to become adults (Figure B13.08).

Figure B13.08: Scientists are not sure why zebras have stripes, but some research suggests it makes them less attractive to blood-sucking flies. This spotty foal, however, has a mutation in the gene producing the pattern on its skin. This could make it less likely to survive long enough to reproduce.

3 The best-adapted individuals are more likely to survive and reproduce: Within the population, it is the individuals that have the best adaptive features that have the best chance of surviving and reproducing. We can say that there is a 'struggle for survival' (this does *not* mean that the organisms fight each other). Sometimes, for example, the individuals might have to compete for food if this is in short supply, and only the ones that have the best adaptations for getting food survive.

4 Alleles that confer useful adaptations are more likely to be passed on: These better-adapted individuals are therefore the ones that pass on their alleles to the next generation (Figure B13.09). The alleles that confer the best chance of survival therefore increase in the population, while alleles that are not advantageous become less common.

Most of the time, natural selection does not make anything change. Zebras have stripes because this is a good adaptation that helps them to survive. A mutation that causes a different pattern is not selected for, because it reduces the chance of survival. The allele that causes the spotted pattern in the foal in Figure B13.08 will probably not be passed on to the next generation. The population of zebras will stay striped, not become spotty.

But sometimes, natural selection can cause change in a population. There are two reasons this might happen:

- A new allele could arise, just by chance, by mutation. If this allele gives an organism a better adaptive feature than any of the other individuals in the population, then this organism will be selected for. That is, it will have a good chance of surviving and reproducing. The new allele will be passed on to the next generation.
- The environment could change, so that features that once helped an organism to survive are no longer as useful. For example, as climate change progresses, species that now have plenty of plants to eat and water to drink may find that their environment has become drier. Individuals that have adaptive features that help them to survive in this new environment will pass on their alleles and, over time, there will therefore be changes in the adaptive features of the species.

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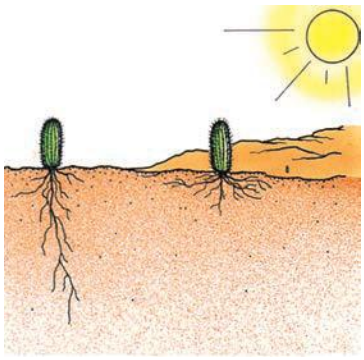
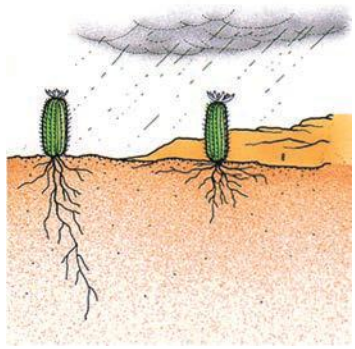
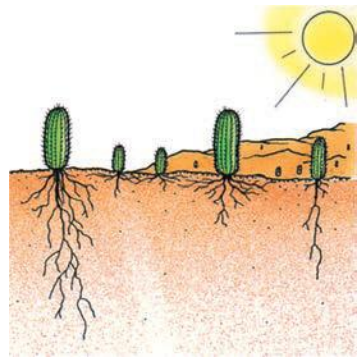


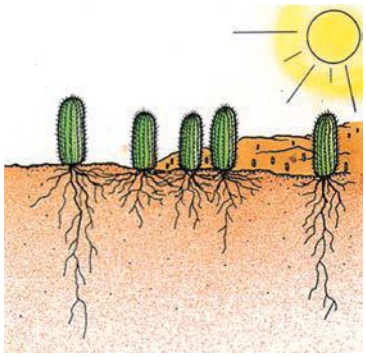
1 Genetic variation. In a population of cacti, some have longer roots than others.



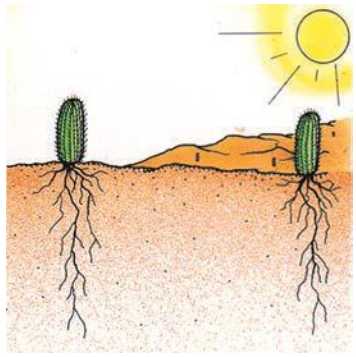
2 In the wet season they flower.



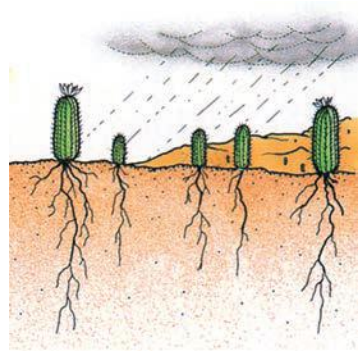
3 Overproduction. The cacti produce large numbers of offspring.



4 Struggle for existence. During the dry season, there is competition for water.



5 Survival of the fittest. The cacti with the longest roots are able to obtain water, while the others die of dehydration.



6 Advantageous characteristics passed on to offspring. The long-rooted cacti reproduce, producing offspring more likely to be long-rooted themselves.

Figure B13.09: How natural selection could affect a population of cacti.

An example of natural selection

Natural selection can help us to understand some changes that took place in the features of a species of moth in Britain and Ireland.

The peppered moth, *Biston betularia*, lives in most parts of Great Britain and Ireland. It flies by night, and spends the daytime resting on tree trunks. It has speckled wings, which camouflage it very effectively on lichen-covered tree trunks (Figure B13.10).

Moth collecting was a fashionable activity in the 19th century, so we know that up until 1849, all the peppered moths in collections were pale and speckled. But in 1849, a dark form of the moth was caught near Manchester. By 1900, 98% of the moths near Manchester were dark. By 1958, there were dark peppered moths in many parts of the country (Figure B13.11).

Figure B13.10: Four peppered moths on a lichen-covered tree trunk. The two normal, speckled moths are on the left. The dark ones are a variation caused by a different allele of the gene for wing colour.

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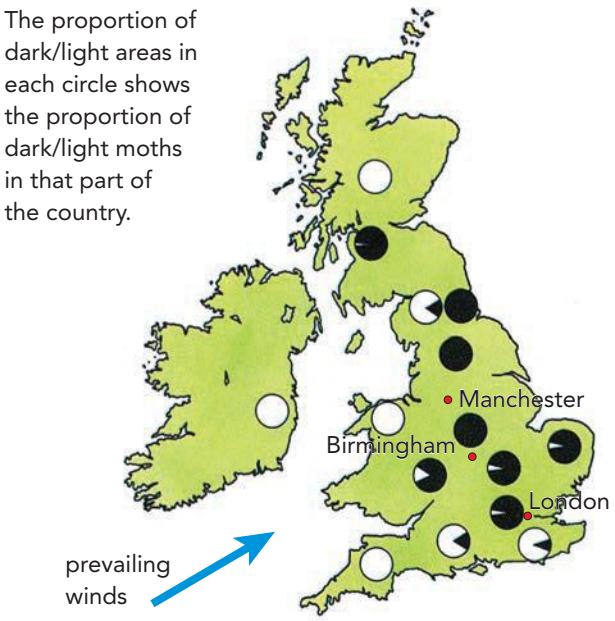

Figure B13.11: The distribution of the pale form and the dark form of the peppered moth in 1958.

How can we explain the sudden rise in numbers of the dark moths, and their distribution today?

We know that the dark colour of the moth is caused by a single dominant allele of a gene. The mutation from a normal to a dark allele happens fairly often, so it is reasonable to assume that there have always been a few dark moths around, as well as pale speckled ones.

Up until the beginning of the Industrial Revolution, the pale moths had the advantage, as they were better camouflaged on the lichen-covered tree trunks. The pale moths were more likely to survive and reproduce, so the allele producing the pale colour was much more common than the allele for dark wings.

But in the middle of the 19th century, some areas of Britain became polluted by smoke. Because the prevailing winds in Britain blow from the west, the worst affected areas were to the east of industrial cities such as Manchester and Birmingham. The polluted air prevented lichens from growing. Dark moths were now better camouflaged than pale moths on trees with no lichens on them.

KEY WORDS

selection pressure: something in the environment that affects the chance that individuals with different features will survive and reproduce.

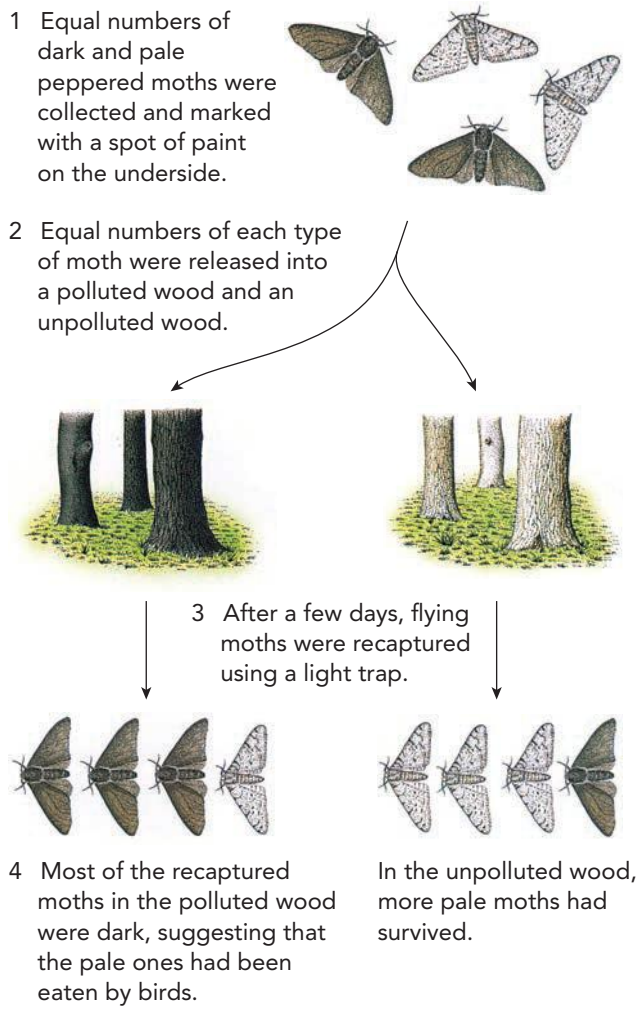

Figure B13.12: An investigation to measure the survival of dark and pale peppered moths in polluted and unpolluted environments.

Proof that the dark moths do have an advantage in polluted areas has been supplied by several investigations. Figure B13.12 summarises one of them.

The factor that gives an advantage to the dark moths, and a disadvantage to the pale moths in polluted areas, is predation by birds. This is called a **selection pressure**, because it 'selects' the dark moths for survival. In unpolluted areas, the pale moths are more likely to survive.

Questions

B13.05 Look at the four numbered points summarising how natural selection happens, near the beginning of Topic B13.02 Selection.

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Use these four points to summarise how selection caused the proportion of dark peppered moths near Manchester to increase at the end of the 19th century.

B13.06 Today, in the 21st century, air quality in Britain is much better than it was in the past. It is now very rare to see a dark peppered moth in Britain.

Explain how selection has caused this reversal in the proportions of pale and dark peppered moths in the population.

ACTIVITY B13.01

Modelling natural selection

Work in a group of two or three for this activity.

You will need:

- a spoon
- a pair of tweezers
- test-tube holder
- a pair of scissors
- a small cup or dish
- elastic bands
- toothpicks
- dried pasta
- paper clips
- stopwatch.

Each of the items you can hold things with represents a bird's beak. The other items represent different types of food.

Method

1. Arrange the four items representing model food (elastic bands, toothpicks, dried pasta and paper clips) into four piles on the desk, spaced out from one another.
2. One member of the group must then use one item representing a model beak (spoon, tweezers, test-tube holder or scissors) to pick up as many of the individual types of food item in ten seconds and transfer them to the small cup/dish.
3. Repeat this for each of the four types of food item, and then for each of the four types of beak.
4. Draw a table to show the results. It should have space to write 12 pieces of data.
5. Take it in turns in your group to repeat this investigation.
6. Calculate mean values for each of the types of beak, and each of the types of food.

CONTINUED

Questions

1. How did the method you followed increase the reliability of the data in this investigation?
2. What are the differences between the model beaks that help you pick up the different types of model food?
3. Can you think of another item that could be used to pick up a specific type of model food that could be more effective?

Self assessment

How did you work with your partners? Next time, would you organise yourselves differently to make better use of the time available?

Reflection

Natural selection is a process that does not normally occur in one generation. How could you improve this investigation to show the effect of natural selection over a long period of time?

Selective breeding

Humans can bring about changes in living organisms, by selecting certain individuals for breeding.

For example, from the varied individuals among a herd of cattle, the breeder chooses the ones with the characteristics he or she wants to appear in the next generation. He or she then allows these individuals, and not the others, to breed. If this selection process is repeated over many generations, these characteristics will become the most common ones in the population.

The process of choosing only certain animals or plants to breed is called **artificial selection or selective breeding**. It has been going on for thousands of years, ever since humans first began to cultivate plants and to domesticate animals. It works in just the same way as natural selection. Individuals with 'advantageous' characteristics breed, while those with 'disadvantageous' ones do not.

KEY WORDS

artificial selection or selective breeding: choosing particular organisms with desired characteristics to breed together, and continuing this over many generations.

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Even when a particular breed has been produced, farmers will still continue to use selective breeding to enhance the characteristics that they choose. Imagine, for example, that a farmer has a herd of cows, which she keeps for milk production. She wants to improve her herd. She will follow these steps:

1 Choose only the cows that produce large volumes of high-quality milk.

2 Choose a bull whose mother, sisters and/or daughters produce large volumes of high-quality milk.

3 Breed the chosen cows with the chosen bull.

4 Allow the calves to grow to adults. From this generation, select the cows that produce the greatest volumes of high-quality milk, and breed them with the chosen bull (which could be the same one, or a different one).

5 Repeat for many generations.

Sometimes, the breeder may want to combine two useful characteristics. So, she might, for example, choose to breed a cow that produces high-quality milk with a bull that is very docile (calm and easy to handle). If she repeats this over several generations, she should be able to produce cows that are both easy to handle, and good milk producers.

Note that the features chosen for selective breeding are what the breeder wants. These features might actually make it *less* likely that the organism could survive in the wild (Figure B13.13).

Figure B13.13: This Merino sheep got lost, so his wool was not removed by a farmer for many years. Merino sheep have been selectively bred to produce a lot of wool, and his wool weighed so much that he almost died. He was eventually found and his wool removed.

Questions

B13.07 Sheep produce methane, which is a greenhouse gas. In New Zealand, farmers are using selective breeding to produce flocks of sheep that produce less methane. Outline how they can do this.

B13.08 Wheat is a cereal crop that is attacked by many different pests, including a fungus called yellow rust. Some varieties of wheat have quite good resistance to yellow rust, but do not produce high yields.

a Describe how you could use selective breeding to produce a new variety of wheat that has good resistance to yellow rust and produces high yields.

b When resistant varieties of wheat are produced by selective breeding, it is often found that, after a few years, they are infected by yellow rust again.

Explain how natural selection might cause the yellow rust to become able to infect the resistant varieties of wheat.

B13.03 Drugs

When someone is ill, we can often use **drugs** to help to ease their symptoms, or to help them to recover. A drug is a substance that affects metabolic reactions in the body. Drugs that help us to stay healthy are called medicinal drugs.

Antibiotics

Antibiotics are medicinal drugs that kill bacteria in the body, without harming our own cells. They are a very important tool in medicine. Antibiotics help to cure bacterial infections that could otherwise be very serious or even fatal. Antibiotics do not, however, affect viruses, so there is no point in using them to treat viral infections such as colds.

KEY WORDS

drug: any substance taken into the body that modifies or affects chemical reactions in the body.

antibiotic: a substance that is taken into the body, and which kills bacteria but does not affect human cells or viruses.

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Penicillin is an antibiotic that stops bacteria from forming cell walls (Figure B13.14). When a person infected with bacteria is treated with penicillin, the bacteria are unable to grow new cell walls, and they burst open.

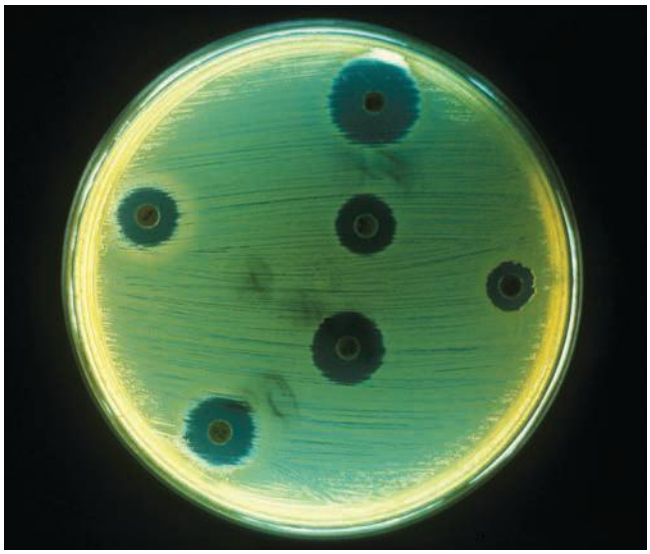


Figure B13.14: This Petri dish contains agar jelly on which the bacteria are growing. The six black circles are small discs of filter paper soaked in different antibiotics. You can see how the bacteria are unable to grow close to the discs, showing that these antibiotics are effective against the bacteria.

Antibiotic resistance

Over the last few decades many populations of pathogenic bacteria have become resistant to antibiotics. These resistant bacteria are no longer killed by the antibiotics, so the effectiveness of the antibiotics is reduced.

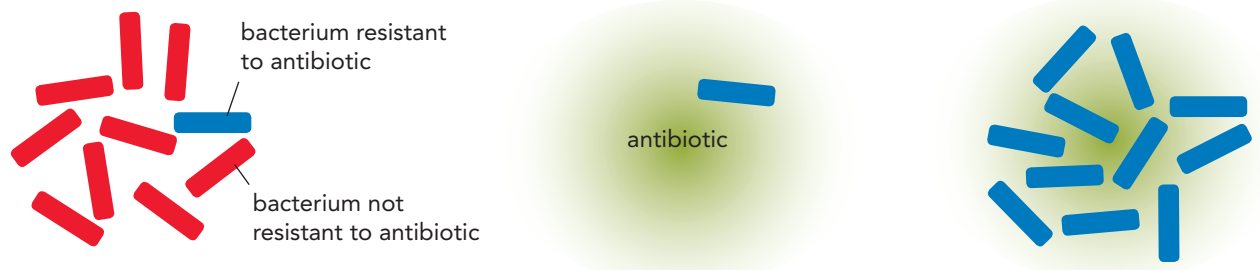
This has happened by natural selection, a process you encountered earlier in this chapter. This is because this feature increases the ability of the bacteria to survive and reproduce. The population of bacteria in a person's body may contain several million individuals. Within that population, there are likely to be at least one or two individuals that have an allele that makes them resistant to penicillin. These individuals will have a tremendous selective advantage. They will be able to go on reproducing while all the others cannot. Soon, their descendants – all containing the allele that confers resistance to penicillin – may form a huge population of penicillin-resistant bacteria (Figure B13.15).

This does, in fact, happen quite frequently. This is one reason why there are so many different antibiotics available. If some bacteria become resistant to one, they can be treated with another.

Over the last few decades, however, many populations of pathogenic bacteria have become resistant to antibiotics. These resistant bacteria are no longer killed by the antibiotics.

MRSA

Today, there are many populations of bacteria that have become resistant to more than one antibiotic. One example is the bacterium *Staphylococcus aureus*. *S. aureus* lives on the skin of most of us and is normally completely harmless, but it can sometimes cause dangerous infections if it gets through the skin and into the body. In the past, it was easy to treat these infections, because *S. aureus* could be killed with many different antibiotics, including penicillin, oxacillin, amoxicillin and methicillin.



In a population of bacteria, not every one is alike. By chance, one may have an allele that makes it resistant to an antibiotic.

Antibiotic is added, which kills the bacteria that are not resistant.

The resistant one multiplies and forms a population of resistant bacteria just like itself.

Figure B13.15: Populations of bacteria become resistant to antibiotics through natural selection.

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These resistant populations are given the name **MRSA**, standing for methicillin-resistant *Staphylococcus aureus*. Doctors do still have a few antibiotics that can kill MRSA, but this bacterium is constantly adapting to its new environmental pressures. It is a kind of race – the bacterium develops, through random mutation and natural selection, a new adaptation that helps it to survive treatment with antibiotics, and we then find new antibiotics to treat it with. The bacterium then becomes resistant to the new antibiotic, and so on.

The more we use antibiotics, the more likely it is that resistant populations of bacteria will develop. It is very important to restrict the use of antibiotics as much as we can. Of course, if someone has a serious bacterial infection, they need antibiotics to help them to recover. But it is pointless to give someone antibiotics for a cold or for a minor bacterial infection that the body can fight off on its own. Reducing our use of antibiotics means that bacteria that have resistance to them have no selective advantage, so populations of resistant bacteria are much less likely to arise. Then, when someone really does need to be treated with the antibiotic, it will work.

KEY WORD

MRSA: methicillin-resistant *Staphylococcus aureus*; bacteria that are resistant to the antibiotic methicillin.

PROJECT B13.01 USING BEADS TO INVESTIGATE THE EFFECTS OF SELECTION

How do so many different types of vegetables arise from one type of plant? Specific selection pressures can lead to changes in phenotypes and produce a wide range of new breeds. In the case of brassicas, artificial selection for specific characteristics has produced six different vegetables (Figure B13.16).

In this project, you are going to use beads to model natural or artificial selection. In Chapter B12, you may have used different colours of beans or beads to represent alleles in Activity B12.02 Breeding beads. In this project, we are going to do something similar, but with some important changes to the procedure.

You will use the beads in the same way as in that activity, to model how alleles are passed on from one generation to the next, and to predict the ratios of the different genotypes and phenotypes in the next generation. However, this time, you are going to apply a selection pressure *against* a specific genotype to each 'generation' of beads.

Here is how to do this:

- Put 100 red beads and 100 yellow beads (or whatever colours you have) into a large beaker. This is your population of organisms. The beads represent the alleles in the gametes that they make. Red beads represent allele **A**, and yellow beads represent allele **a**.
- Without looking, pick out two beads from the container. These represent the result of two individuals in the population mating. Record the genotype of the offspring you have just produced. Put these beads into another container.
- Keep doing this until you have used up all the beads in your initial population.
- Write down the number of organisms of each genotype that you have produced in the next generation.
- Now let your new generation breed, just as the first one did. But this time, apply a selection pressure to the **aa** offspring. Let's say that one in five of them do not survive to reproduce.
- To model this, remove every fifth offspring with the genotype **aa** from your populations. (That is, put every fifth pair of yellow beads – **aa** – into a different container as soon as they appear and ignore them from now on – they are dead.) Record your results again.

CONTINUED

- Keep going, repeating your one in five selection against the **aa** offspring, for several generations.

Other groups could try different selection pressures, like this:

Selection pressure against homozygous recessive individuals	What you do
5%	Remove every 20th **aa** offspring from the population
10%	Remove every 10th **aa** offspring from the population
20%	Remove every 5th **aa** offspring from the population
25%	Remove every 4th **aa** offspring from the population
50%	Remove every 2nd **aa** offspring from the population
100%	Remove every **aa** offspring from the population

When all the groups have collected results, discuss what you have found. Here are two issues you may like to discuss:

1 How do your selection pressures affect the proportion of homozygous recessive organisms in the population? Do they ever disappear completely?

2 How well do you think this model represents what really happens in a population of organisms?

SUMMARY

Differences between individuals of the same species are called variation.
Continuous variation occurs when an individual can have any phenotype in a complete range between the two extremes. There are no distinct categories. Human height and body mass are examples of continuous variation.
Discontinuous variation occurs when there is a limited number of phenotypes, such as the A, B, AB and O blood groups in humans. It is caused by genes alone.
Mutation is genetic change. It is the way that new alleles are formed.
Gene mutation is a random change in the base sequence of DNA.
Natural selection acts on variation among the individuals in a population. More offspring are produced than will survive to adulthood, and those individuals with the best adaptations to their environment are more likely to survive long enough to reproduce. We can say that there is a 'struggle for survival', including competition for resources such as food supply. The best-adapted individuals are therefore more likely to pass on their alleles to the next generation.
Adaptation is the process, resulting from natural selection, by which populations become better adapted to survive and reproduce in their environment, over many generations.
Selective breeding involves humans selecting individual animals or plants with desirable features to breed together, repeating this process with the offspring, and then repeating again for several generations. It is used to improve crop plants and domestic animals.
A drug is any substance taken into the body that modifies or affects chemical reactions in the body.

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CONTINUED

Antibiotics are used for the treatment of bacterial infections, but not viral infections. However, some bacteria are resistant to antibiotics, which reduces the effectiveness of antibiotics.
Using antibiotics only when essential can limit the development of resistant bacteria such as MRSA.

PRACTICE QUESTIONS

1 How are new alleles formed?

A by artificial selection
B by continuous variation
C by discontinuous variation
D by mutation **[1]**

2 Identify which process almost always results in adaptation to the environment.

A artificial selection
B mutation
C natural selection
D selective breeding **[1]**

3 Complete the following sentences.

a Variation can be defined as differences between individuals belonging to the same _____ . **[1]**

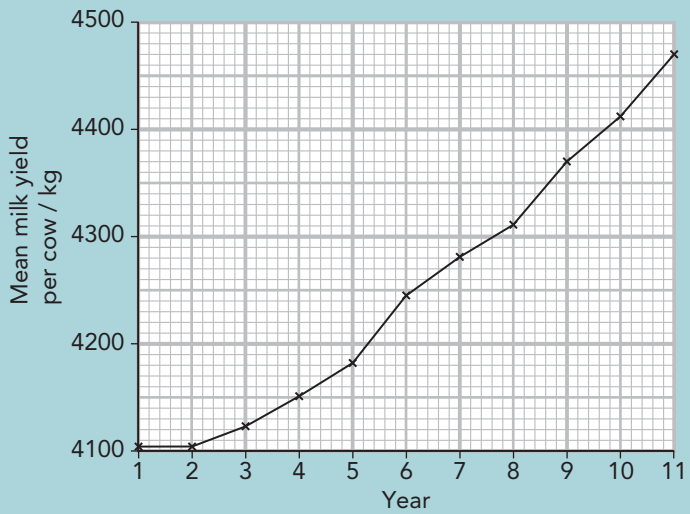
b Sometimes, the differences are clear-cut, and each individual fits into one of a small number of defined categories. This is called _____ variation. **[1]**

c In other cases, the differences have no definite categories. This is called _____ variation. **[1]**

[Total: 3]

4 A farmer used selective breeding to try to improve the milk yield in her herd of cows.

The graph below shows the mean yield of milk per cow over the 12 years that the farmer carried out selective breeding.



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CONTINUED

a **Describe** the changes in mean milk yield during the selective breeding programme. **[2]**

b Describe how the breeder would have carried out the breeding programme. **[2]**

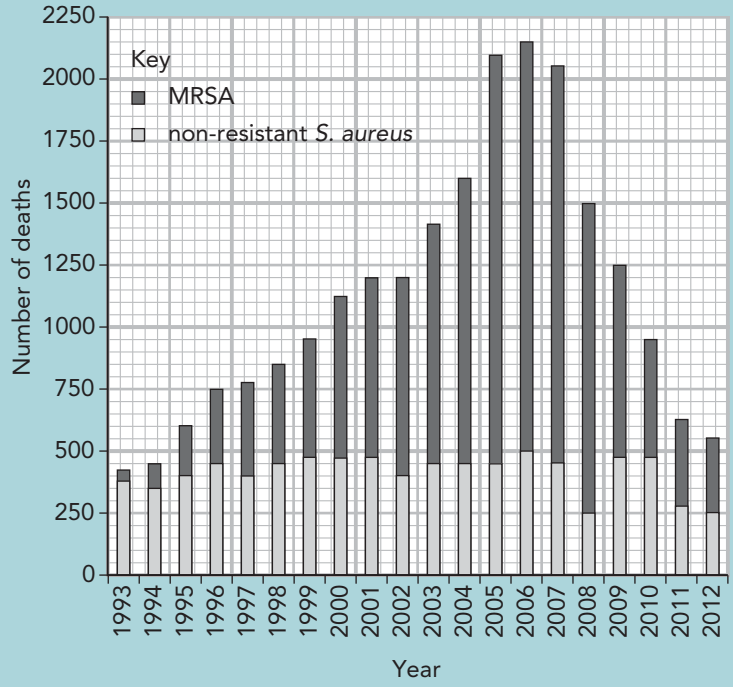
c **Explain** why the breeder does not need to know anything about the genes that affect milk production, in order to carry out a successful breeding programme. **[2]**

d The mean percentage protein content of the milk in year 1 was 3.83.

This steadily fell, reaching 3.79 in year 12. **Suggest** why this happened. **[1]**

[Total: 7]

5 The graph below shows the number of deaths caused by MRSA and by non-resistant *Staphylococcus aureus* in a European country between 1993 and 2012.



a Describe the changes in the number of deaths from MRSA between 1993 and 2012. **[2]**

b The percentage of deaths from *S. aureus* that were caused by MRSA in 1993 was 8.3%.

Calculate the percentage of deaths from *S. aureus* that were caused by MRSA in 2006. **[1]**

c In 2006, new procedures were introduced into hospitals to try to prevent the increase in cases of MRSA.

Suggest and explain *two* changes that could have helped to cause the subsequent change in the number of cases of MRSA shown on the graph. **[4]**

[Total: 7]

COMMAND WORDS

describe: state the points of a topic/give characteristics and main features.

explain: set out purposes or reasons/ make the relationships between things evident/provide why and/or how and support with relevant evidence.

suggest: apply knowledge and understanding to situations where there is a range of valid responses in order to make proposals/put forward considerations.

COMMAND WORD

calculate: work out from given facts, figures or information.

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CONTINUED

6 Gene mutation is a source of genetic variation in a population.

a **Define** *gene mutation*. **[1]**

b **State** *two* factors that can increase the rate of gene mutation. **[2]**

[Total: 3]

COMMAND WORDS

define: give a precise meaning.

state: express in clear terms.

SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
describe variation as differences between individuals belonging to the same species	B13.01			
explain the differences between continuous variation and discontinuous variation, and give examples	B13.01			
investigate, record and analyse examples of continuous and discontinuous variation	B13.01			
state that mutation is the way that new alleles are formed	B13.01			
describe gene mutation as a random change in the base sequence of DNA	B13.01			
describe natural selection resulting from variation, overproduction of offspring, struggle for survival (including competition), reproduction by organisms with better adaptations, and the passing on of their alleles to the next generation	B13.02			
describe how selective breeding is done, and how it can be used to improve crop plants and domesticated animals	B13.02			
describe a drug as any substance taken into the body that modifies or affects chemical reactions in the body	B13.03			
describe the use of antibiotics for the treatment of bacterial infections, but not viral infections	B13.03			
state that some bacteria are resistant to antibiotics, which reduces the effectiveness of antibiotics	B13.03			
explain how using antibiotics only when essential can limit the development of resistant bacteria such as MRSA.	B13.03			

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B14

Organisms and their environment

All learners study all content in this chapter

IN THIS CHAPTER YOU WILL:

- explain how energy is transferred through food webs and back to the environment
- learn about food chains and food webs
- describe the human impacts of overharvesting and introducing foreign species to a habitat
- describe the carbon cycle in ecosystems.

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BEFORE YOU START

- Ask one person in your class to write the name of a plant or animal on the board.
- Now, another person writes the name of a plant or animal that eats, or is eaten by, the first one, and adds an arrow to show how energy transfers from one to the other.
- Continue like this, until your class has constructed a really big food web on the board.

SCIENCE IN CONTEXT B14.01

A fossil food chain

About 250 million years ago, there was a huge supercontinent on Earth, called Pangaea. The centre of this enormous landmass was so far from the sea that rain rarely fell. Later, as the plates that make up the Earth's crust drifted apart, Pangaea broke up. Some of the northern areas became what is now Russia.

We know something about the animals that lived in this area at that time, because we have found their fossils. We know that there were herbivores that ate vegetation, and carnivores that fed on the herbivores. We can work this out from their skeletons and teeth. For example, if an animal has broad, flat teeth with ridges on them, this suggests it was adapted to feed on plants. If its teeth were pointed and sharp, this suggests it killed and ate other animals.

It is difficult, though, to be certain exactly what any one species ate, and we have only limited evidence about the food chains and food webs that might have existed 250 million years ago in this part of the world.

One strong possibility is that a carnivore called *Inostrancevia* preyed on a herbivore called *Scutosaurus* (Figure B14.01). Fossils of both of these dinosaurs are found in similar areas, and date from the same time. *Inostrancevia* was probably the apex (top) predator at the time. It was up to 3.5 m long and had a huge skull with upper canines that grew to 15 cm long.

Figure B14.01: *Inostrancevia* and *Scutosaurus*.

Discussion questions

1 How do you think scientists can work out food chains and food webs today? What evidence can they use, and how might they collect this evidence?

2 How does this differ from the kind of evidence that scientists can use to try to construct food chains and food webs in the distant past?

B14.01 Energy flow

All living organisms need energy. All the energy in an ecosystem originates from the Sun. Some of the energy in sunlight is captured by plants, and used to make organic nutrients – glucose, starch and other organic substances such as fats and proteins. These contain some of the energy from the sunlight. When a plant cell needs energy, it breaks down some of this food by respiration.

So where does the energy in organisms other than plants come from? Animals that consume plants obtain their energy directly from the organic nutrients in the plant tissues. When other animals feed on these animals, they obtain energy from them.

B14.02 Food chains and food webs

Animals get their food, and therefore their energy, by ingesting (eating) plants, or by eating animals which have eaten plants. Again, when a cell needs energy to carry out a particular process, such as muscle contraction or active transport, the energy is released by respiration.

The sequence by which energy, in the form of chemical energy in food, passes from a plant to an animal and then to other animals, is called a **food chain**. Figure B14.02 shows one example of a food chain.

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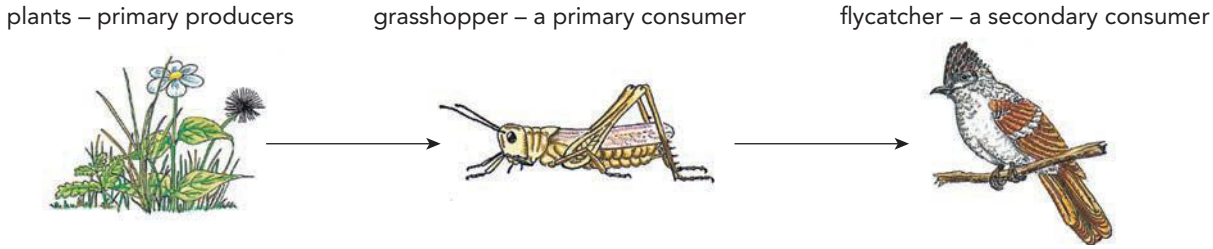

Figure B14.02: A food chain.

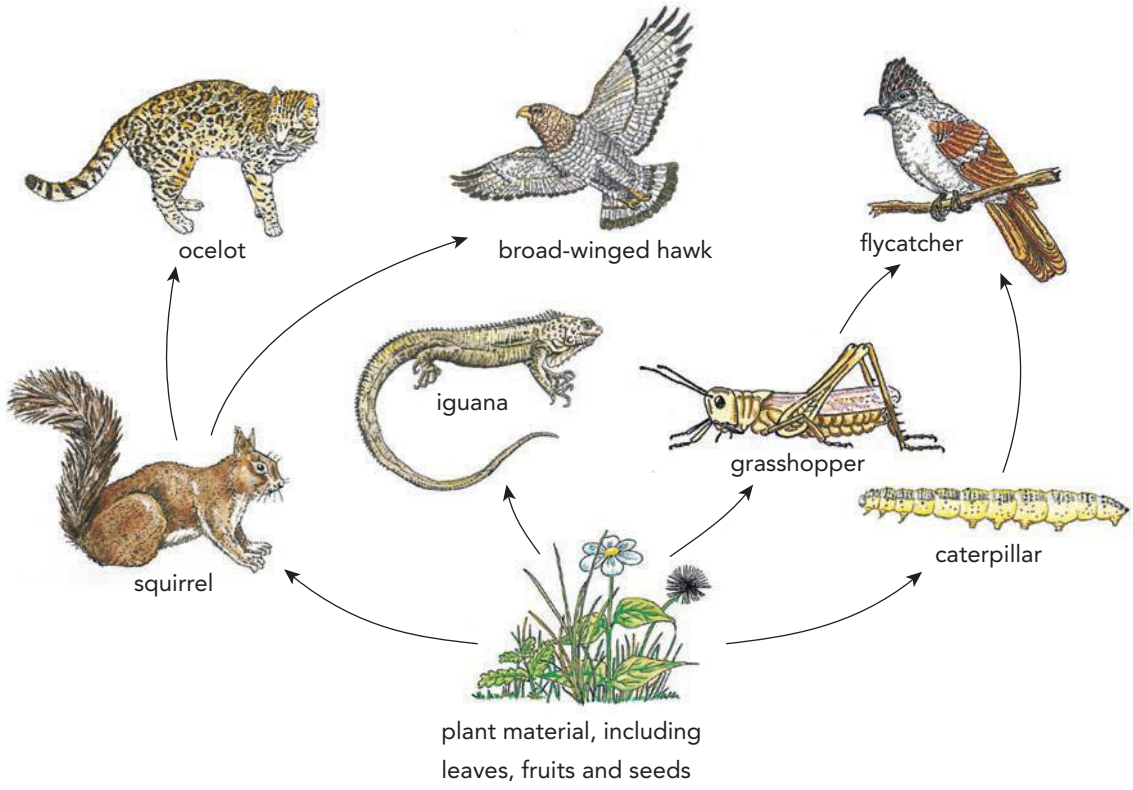

Figure B14.03: A food web.

Many different food chains link to form a **food web**. Figure B14.03 shows an example of a food web.

Producers and consumers

Every food chain begins with green plants because only they can capture the energy from sunlight. They are called **producers** because they produce the energy-containing organic nutrients that all the other organisms in the food chain need.

KEY WORDS

food chain: a diagram showing the flow of energy from one organism to the next, beginning with a producer.

food web: a network of interconnected food chains.

producer: an organism that makes its own organic nutrients, generally using energy from sunlight, through photosynthesis.

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Animals are **consumers**. An animal that gets its energy by eating plants is a **primary consumer**, because it is the first consumer in a food chain. An animal which eats that animal is a **secondary consumer**. An animal that eats a secondary consumer is a **tertiary consumer**. Primary consumers are also called **herbivores**, and consumers that eat other animals are called **carnivores**.

Fungi are also consumers. They get their energy by feeding on dead and decaying bodies and waste organic material from plants and animals. Consumers that feed like this are called **decomposers**.

KEY WORDS

consumer: an organism that gets its energy by feeding on other organisms.

primary consumer: an animal that gets its energy by eating plants; it is the first consumer in a food chain.

secondary consumer: an animal that eats a primary consumer.

tertiary consumer: an animal that eats a secondary consumer.

herbivore: an animal that gets its energy by eating plants.

carnivore: an animal that gets its energy by eating other animals.

decomposer: an organism that gets its energy from dead or waste organic material.

ACTIVITY B14.01

Matching ecology terms

Work in a small group for this activity.

You need 26 identical pieces of card. On one side of 13 of them, write one of the key words you have met in this chapter. On one side of the other 13, write the meanings of these key words.

Shuffle the cards. Place them all upside down on the table and spread them out.

The first person turns over a card, and reads what it says. Everyone in the group must be able to see that card. The same person then turns over another card and reads what that card says.

If the two cards give a word and its meaning, the person keeps the cards and has another go. If the two cards do not match, then the cards are turned face down again, in their original positions. The next person then takes their turn.

The winner is the person with the most cards when all 26 cards have been matched.

Questions

B14.01 In a desert, kangaroo rats eat seeds of creosote bushes. Some of the kangaroo rats are eaten by kit foxes (Figure B14.04). Coyotes eat kit foxes.

- **a** Show this information as a food chain. (You do not need to draw the organisms – just write their names.)
- **b** Name the producer in this food chain.
- **c** Identify the primary consumer, secondary consumer and tertiary consumer in this food chain.
- **d** Which organisms in the food chain are herbivores? Which are carnivores?
- **e** Leaves of creosote bushes are also eaten by grasshoppers and jackrabbits. Kit foxes also eat jackrabbits. Grasshoppers are eaten by kit foxes and tarantulas.

  Add this information to your food chain, to make a food web.

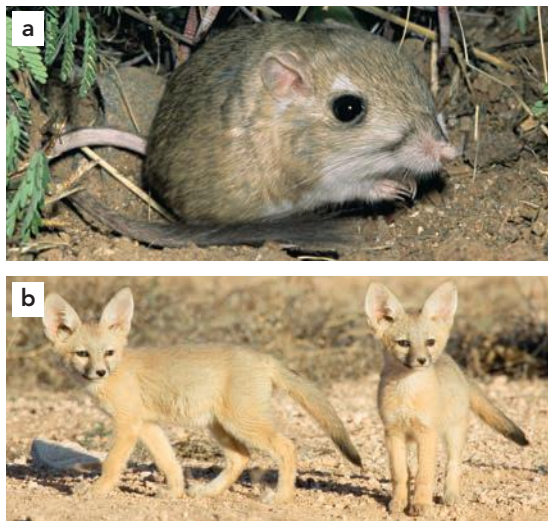

Figure B14.04 a: A kangaroo rat. **b:** Kit foxes.

B14.02 Construct a food chain of your own, with a human at the end of it. Label your food chain to show the producer, and also the different levels of consumers.

B14.03 Most food chains have only a few links, and it is very rare to find a food chain that has more than five links in it. Suggest an explanation for this.

Energy losses

As energy is passed along a food chain, some of it is lost to the environment. This happens in several ways (Figure B14.05).

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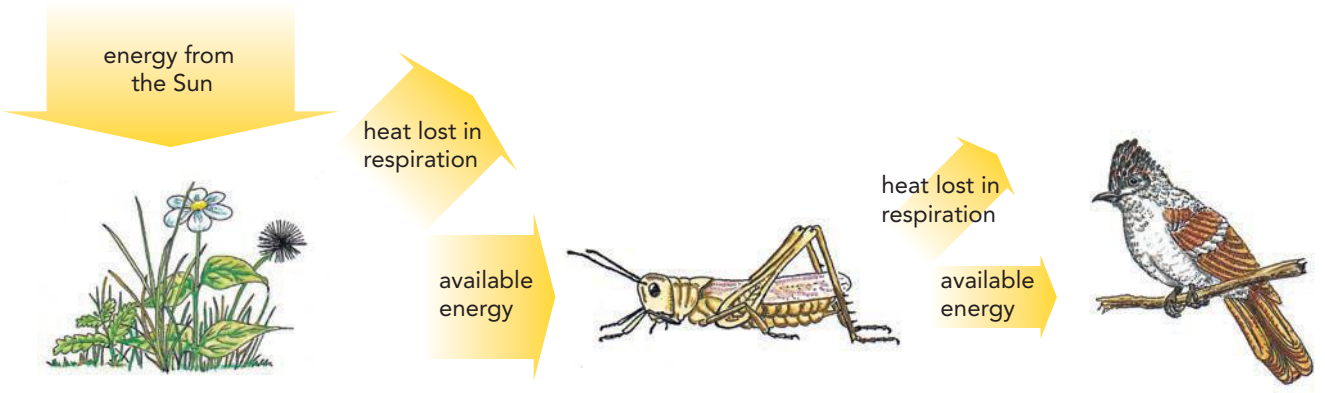

Figure B14.05: Energy is lost to the environment as it passes along a food chain.

- When an organism uses glucose and other organic compounds for respiration, some of the energy released from the glucose is lost as heat energy to the environment.
- When one organism eats another, it rarely eats absolutely all of it. For example, the grasshopper in the food chain in Figure B14.05 may eat almost all of the parts of the plant above ground, but it will not eat the roots. So not all of the energy in the plant is transferred to the grasshopper.
- When an animal eats another organism, enzymes in its digestive system break down most of the large nutrient molecules, so that they can be absorbed. But not all of the nutrient molecules are digested and absorbed. Some just pass through the alimentary canal and are eventually lost from the body in the faeces. These faeces contain energy that is lost from this food chain.

This means, the further you go along a food chain, the less energy is available for each successive group of organisms. In Figure B14.05, the plants get a lot of energy from the Sun, but only a fraction of this energy is absorbed by the grasshoppers, and only a fraction of that is absorbed by the flycatcher birds.

We can think of energy as flowing from the Sun as energy in light, then through a food chain in the form of chemical energy in organic nutrients, and finally back to the environment as heat energy.

Trophic levels

If we count the numbers of organisms at different positions in a food chain, we usually find that there are more plants than animals, and more herbivores than carnivores. Each level in a food chain is called a **trophic level** ('trophic' means feeding).

KEY WORDS

trophic level: the position of an organism in a food chain, food web or pyramid of biomass or numbers.

There is less energy available as you go up the trophic levels, so there are fewer organisms at each level. There is a lot of energy for the plants in this ecosystem. The grasshoppers that eat the plants do not get all of this energy, because most is lost to the environment. This means that there cannot be as many grasshoppers as there are plants – there is simply not enough energy to support them.

In the same way, the flycatchers only receive a small proportion of the energy that the grasshoppers contain. Only enough energy reaches the flycatchers to support a small population of them.

Many organisms feed at more than one trophic level. You, for example, are a primary consumer when you eat vegetables, a secondary consumer when you eat meat or drink milk, and a tertiary consumer when you eat a predatory fish such as a salmon.

Efficiency of energy transfer

Understanding how energy is passed along a food chain can be useful in agriculture. Humans can eat a wide variety of foods, and can feed at several different trophic levels. Which is the most efficient sort of food for a farmer to grow, and for us to eat?

The nearer to the beginning of the food chain we feed, the more energy there is available for us. This is why our staple foods, such as wheat, rice and potatoes, are plants.

When we eat meat, eggs or cheese or drink milk, we are feeding further along the food chain. There is less energy

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available for us from the original energy provided by the Sun. It would be more efficient, in principle, for humans to eat the grass in a field, rather than to let cattle eat it, and then to eat them. But although there is far more energy in the grass than in the cattle, it is not available to us. We simply cannot digest the cellulose in grass, so we cannot release the energy from it. The cattle can. They turn the energy in cellulose into energy in protein and fat, which we can digest.

However, there are many plant products which we can eat. Soya beans, for example, yield a large amount of protein much more efficiently and cheaply than cattle or other animals. It is not energy efficient to feed soya beans to cattle, and then eat the cattle.

Question

B14.04 Figure B14.06 shows a dairy farm. This is in a desert region, where there is no grass for cattle to graze. Instead, the cattle are fed on soya beans.

Explain why this is not an energy-efficient way of producing food for humans.

Figure B14.06: A dairy farm.

Overharvesting and foreign species

Food chains and food webs are vulnerable to change, brought about by some human activities.

Humans have always hunted and harvested animals and plants for food, but sometimes this hunting or harvesting is so severe that it can destroy an entire species. There is much evidence that mammoths finally became extinct 5000 years ago because of hunting by humans. The dodo, a giant flightless pigeon that used to live on Mauritius, was destroyed by humans in the late 17th century, when its eggs were eaten and the adults killed. Today, **overharvesting** of some plant and animal species, such as cod, is common. In this case, species eaten by cod increase in numbers, and species which eat cod may begin consuming more individuals from other species.

Another way in which humans have upset the delicate balance of food chains and food webs is by introducing new species to a habitat. These are called **foreign species**. They can disrupt food webs and cause changes in ecosystems that put **native species** (that is, species that naturally live in that area) at risk. For example, New Zealand has been separated from the other land masses on Earth for millions of years. There have never been any mammalian predators there, so many birds are flightless and nest on the ground (Figure B14.07). When the first settlers arrived in New Zealand, about 700 years ago, rats stowed away on their ships. Later, people arriving from Europe brought rabbits to New Zealand to use as food, and then – when the rabbits bred out of control – they introduced stoats to try to reduce the number of rabbits. They also introduced possums from Australia, to farm for fur, but the possums escaped and now there are millions of them living wild in New Zealand. These introduced animals compete with the native ones for food, and also eat the eggs of the ground-nesting birds. Scientists think that 53 species of native birds in New Zealand have become extinct since humans arrived.

Figure B14.07: Many species of bird in New Zealand are flightless, because there have been no predators to exert selection pressures against birds that cannot fly.

KEY WORDS

overharvesting: the unsustainable removal of a crop or animal from its habitat.

foreign species: an organism that is not usually found in a habitat.

native species: an organism that is typical of a particular habitat.

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B14.03 Carbon cycle

Decomposers are a very important group of organisms in an ecosystem. As we have seen, decomposers feed on organic waste material from animals and plants, and on their dead bodies. Many fungi and bacteria are decomposers.

Decomposers are extremely important because they help to release substances from dead organisms. The released substances can then be used by other living organisms. One of these substances is carbon.

Carbon is a very important component of living things, because carbon atoms are part of the molecules of carbohydrates, fats and proteins.

Figure B14.08 shows how carbon circulates through an ecosystem.

About 0.04% of the air is carbon dioxide. When plants photosynthesise, carbon atoms from carbon dioxide become part of glucose and starch molecules in the plant. Some of the glucose is then broken down by the plant in respiration. The carbon in the glucose becomes part of a carbon dioxide molecule again, and is released back into the air. Some of the carbon-containing compounds in the plant will be eaten by animals. The animals respire, releasing some of it back into the air as carbon dioxide.

When the plant or animal dies, decomposers will feed on it. Decomposers also feed on waste materials, such as urine and faeces from animals. The carbon becomes part of the carbon-containing compounds in the decomposers' bodies. When the decomposers respire, they release carbon dioxide into the air again.

Sometimes, however, dead bodies and waste materials are not broken down by decomposers. For example, in places where there is little oxygen such as the seabed in the deep oceans or in waterlogged ground, decomposers may not be able to respire aerobically. Instead, these waste substances become buried in sediments. Over long periods of time, they are gradually changed into coal, oil or natural gas. These are called fossil fuels – not because they contain fossils, but because they were formed millions of years ago, from living organisms. (A true fossil is the remains of an organism that have been turned to stone.)

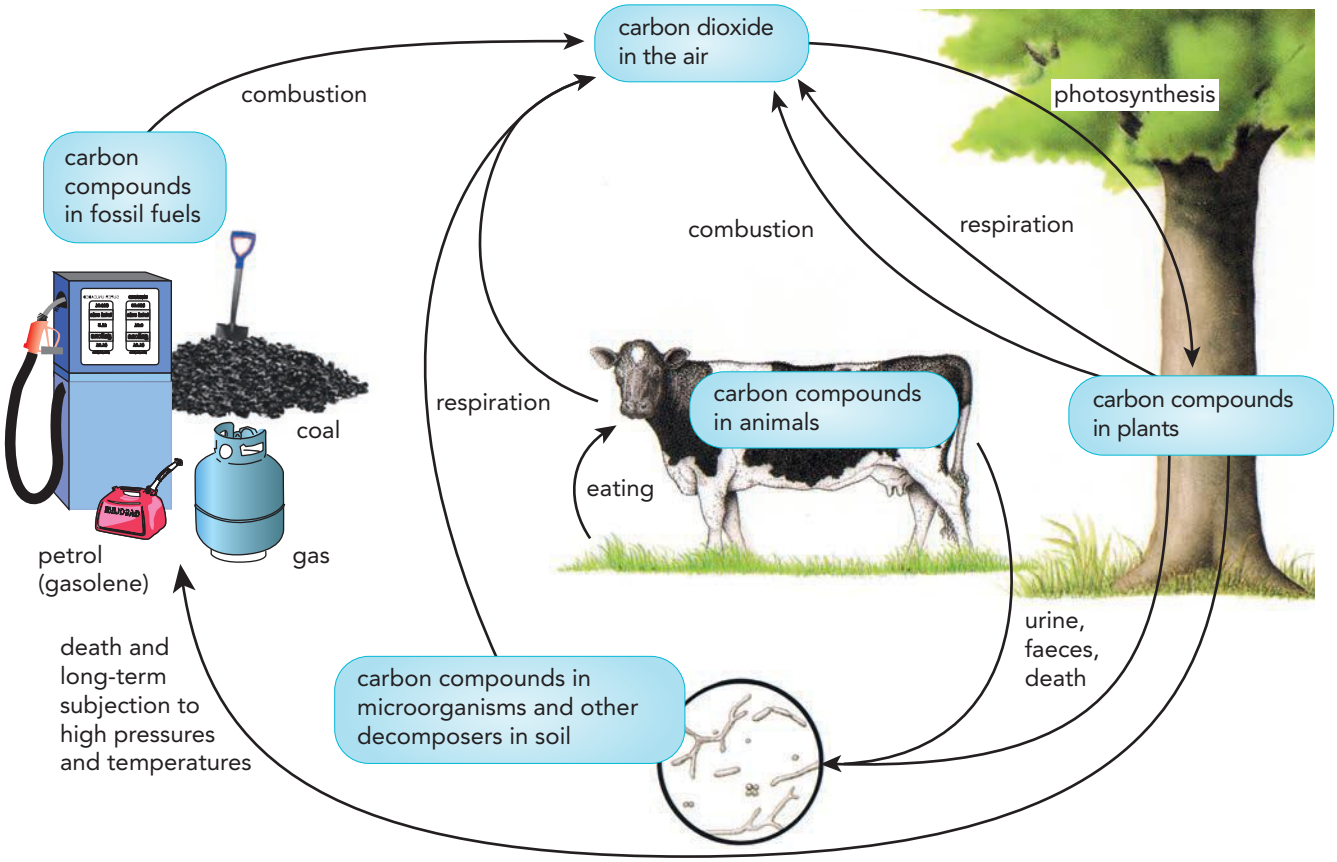

Figure B14.08: The carbon cycle.

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When these fossil fuels are burnt, the carbon in them combines with oxygen from the air, in a process called combustion (Figure B14.09). Wood can also undergo combustion. The carbon and oxygen combine to form carbon dioxide, which is released into the air again.

Figure B14.09: This coal is undergoing combustion.

Questions

B14.05 Look at Figure B14.08.

- **a** List the processes that remove carbon dioxide from the air.
- **b** List the processes that add carbon dioxide to the air.

B14.06 Describe how a carbon atom in a lion could become part of a grass plant.

ACTIVITY B14.02

Modelling the carbon cycle

In this activity, you will use people to represent carbon atoms, and explore how a carbon atom can move around the carbon cycle. It is best to do this activity as a whole class.

Start by looking at Figure B14.08. Choose five areas in the room to represent the five places that a carbon atom can be, shown in blue on the diagram. Label these areas in the room.

Now choose some people to be carbon atoms. Put some carbon atoms in each labelled area.

Someone who is not a carbon atom now calls out one of the processes on a labelled arrow. Some (it is best if it is not all of them) of the carbon atoms affected by this process move to a different place. For example, if the process is 'combustion', some of the carbon atoms in the 'fossil fuel' area move to the 'air' area.

Carry on with this, using different processes at random.

Self assessment

Now that you have completed this activity, how well do you understand the transfers involving atoms in the carbon cycle? Rate yourself for each of the following statements using:

- ☺ if you understand all of the transfers involving a carbon atom
- 😐 if you understand some of the transfers involving a carbon atom
- ☹ if you understand none of the transfers involving a carbon atom

Reflection

Did using this model help you to understand the carbon cycle? Can you explain why it helped or why it did not?

How well do you think the model represents the carbon cycle? Can you think of any ways in which you could refine the model to make it easier to understand?

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PROJECT B14.01 USING SOFTWARE TO ILLUSTRATE A FOOD WEB

You are going to use a computer or tablet to show a food web (Figure B14.10). You will then share what you have done with the rest of the class. This project is best done with a partner.

First, decide on your food web. You could research one in your own area, or you could find information about an interesting food web in a different part of the world.

Next, decide what you will do. This will at least partly depend on what software you have available, and your expertise in using it.

Here are some ideas:

- Simply draw a diagram of a food web, including pictures of the organisms in it. You could label each organism to show which trophic level it is at and whether it is a producer or a primary, secondary or tertiary consumer.
- Add animations to your food web diagram. For example, you could animate the arrows to show energy flowing through the web. You could make your labels interactive, so that they only pop up when the user does something.
- You could produce a series of slides to gradually build up the food web. You could animate some of the slides or the transitions between them.
- You could add an audio commentary explaining what the screen is showing.

You may have other ideas of your own. The aim is not to make things as complicated as possible, but to use what is available to you to produce an attractive and informative representation of a food web, and the ways that energy flows through it.

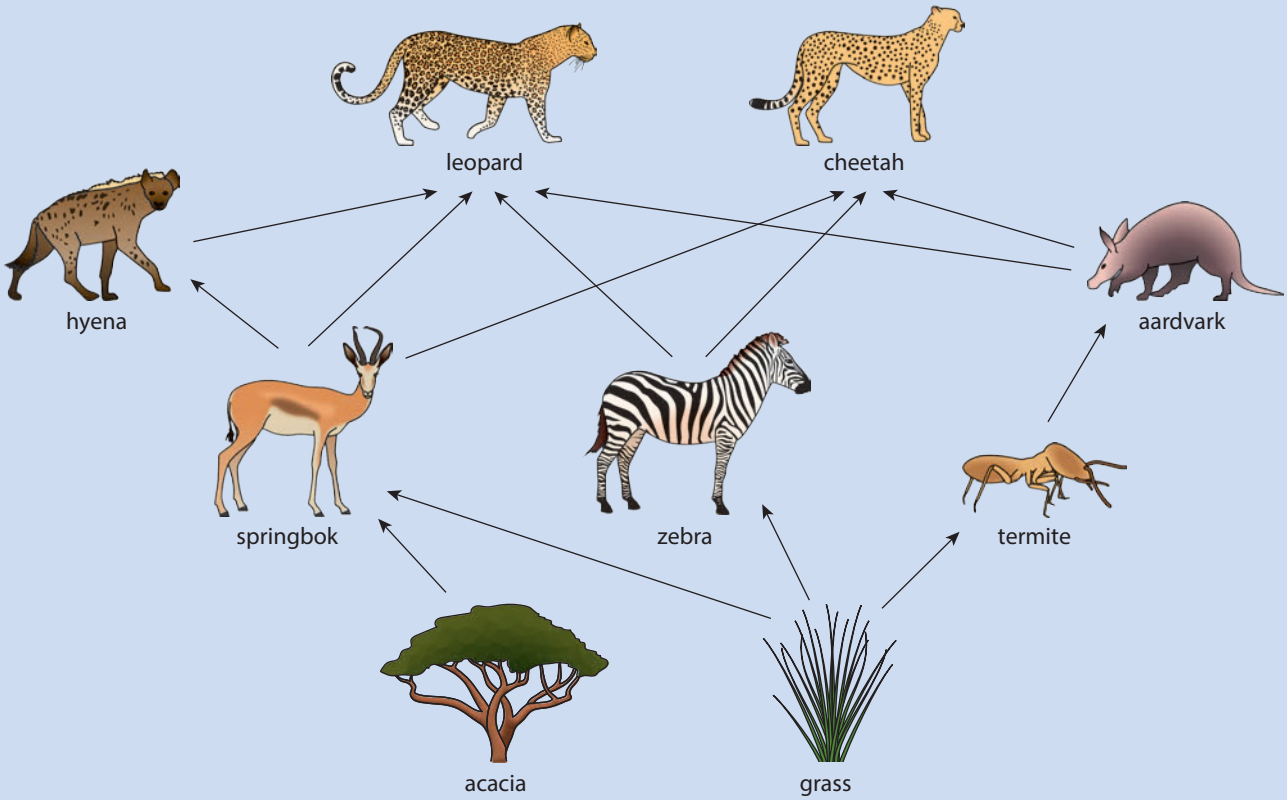

Figure B14.10: An illustrated food web.

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SUMMARY

Biological systems depend on energy that originates from the Sun. A food chain shows how energy is transferred from one organism to another. A food web shows many interconnected food chains.
Energy flows through living organisms, and is eventually lost to the environment. Energy is lost at each step in a food chain.
Producers make their own organic nutrients from inorganic ones by photosynthesis, using energy from sunlight. Consumers get their energy by eating organic nutrients from other organisms. Consumers are classified as primary, secondary, or tertiary consumers, depending on their position in a food chain.
Herbivores are consumers that get their energy by eating plants, while carnivores get their energy by eating animals. Decomposers are consumers that get their energy by feeding on dead organisms, or their organic wastes.
As energy passes along a food chain, some is lost within each organism, and at each transfer between organisms. The main reasons for loss are respiration (which releases some energy as heat), and some of the organisms at one level not being eaten or absorbed by the next level. Energy losses mean that there is rarely sufficient energy to support more than five links in a food chain.
It is more energy efficient for humans to eat crop plants than to eat livestock that have been fed on crop plants.
Food chains and food webs can be used to describe the impact humans have through overharvesting of food species and through introducing foreign species to a habitat.
The carbon cycle summarises how carbon atoms move between organisms and their environment. Photosynthesis removes carbon dioxide from the air. Respiration and combustion return carbon dioxide to the air. Fossil fuels contain carbon atoms that were part of organisms that lived a very long time ago.

PRACTICE QUESTIONS

1 **Identify** the correct definition of a community.

- **A** a group of organisms of the same species, living in the same area at the same time
- **B** all the populations of different species living in the same area at the same time
- **C** a unit containing organisms and their environment, interacting with one another
- **D** the place where a group of organisms is adapted to live **[1]**

2 Organisms that feed at the fifth trophic level are rarer than those that feed at the fourth trophic level. Identify the correct explanation for this.

- **A** Energy is lost to the environment each time it is transferred from one trophic level to the next.
- **B** The biomass of predators is generally larger than their prey.
- **C** There is not usually enough space for large carnivores to survive.
- **D** The populations of large predators are more likely to be limited by disease. **[1]**

COMMAND WORD

identify: name/select/recognise.

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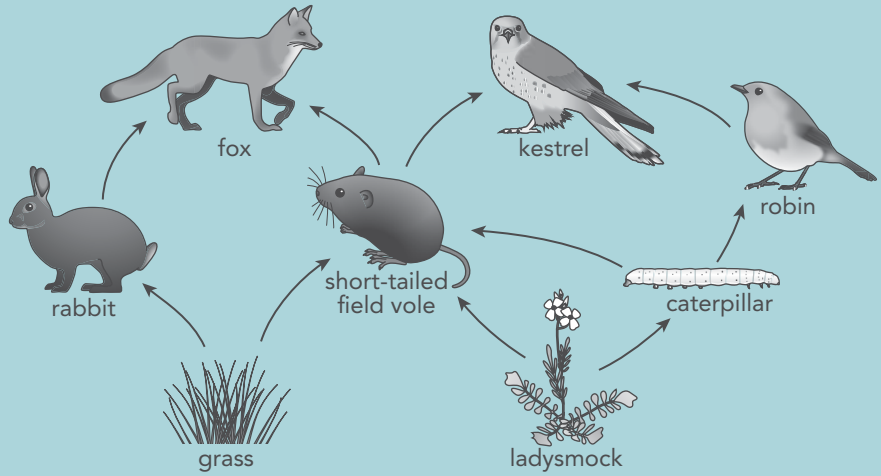
CONTINUED

3 The diagram shows a food web.



a **Explain** what the arrows represent. **[1]**

b Identify *one* producer in this food web. **[1]**

c **Sketch** a food chain containing four organisms, that is part of the food web shown above. **[2]**

d Use the food web to **predict** and explain *two* different ways in which a decrease in the population of short-tailed field voles could affect the population of rabbits. **[4]**

[Total: 8]

4 **a** **Give** an approximate value for the percentage of air that is carbon dioxide. **[1]**

b Give the name of the part of a leaf through which carbon dioxide diffuses. **[1]**

c Give the name of the process that plants use to make glucose. **[1]**

d When animals die, their bodies are broken down. Name this process. **[1]**

e Give the name of the process by which plants, animals and decomposers return carbon dioxide to the air. **[1]**

f **Describe** how fossil fuels are formed, *and* how the carbon in them is returned to the air. **[4]**

[Total: 9]

COMMAND WORDS

explain: set out purposes or reasons/ make the relationships between things evident/provide why and/or how and support with relevant evidence.

sketch: make a simple freehand drawing showing the key features, taking care over proportions.

predict: suggest what may happen based on available information.

give: produce an answer from a given source or recall/memory.

describe: state the points of a topic/give characteristics and main features.

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SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
construct and interpret food chains and food webs, using arrows to show how energy is transferred through them	B14.02			
describe the meanings of the terms *producer, consumer, herbivore, carnivore, decomposer* and *trophic level*	B14.02			
identify producers and consumers in food chains and webs, and classify consumers as primary, secondary, tertiary and quaternary	B14.02			
explain why transfer of energy between trophic levels is inefficient, and use this to explain why food chains rarely have more than five trophic levels, and why it is more energy efficient for humans to eat plants rather than animals	B14.02			
describe the carbon cycle, including photosynthesis, respiration, feeding, decomposition, formation of fossil fuels and combustion.	B14.03			

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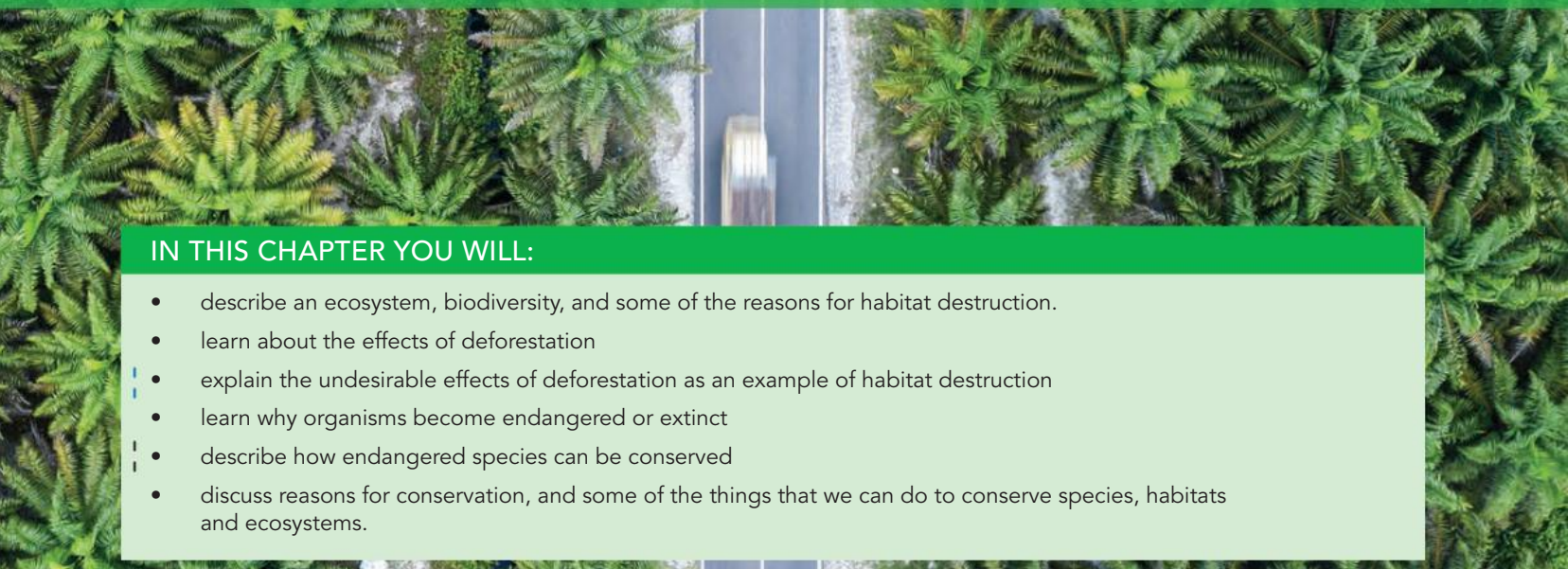
B15

Human influences on ecosystems

All learners study some content in this chapter



IN THIS CHAPTER YOU WILL:

- describe an ecosystem, biodiversity, and some of the reasons for habitat destruction.
- learn about the effects of deforestation
- explain the undesirable effects of deforestation as an example of habitat destruction
- learn why organisms become endangered or extinct
- describe how endangered species can be conserved
- discuss reasons for conservation, and some of the things that we can do to conserve species, habitats and ecosystems.

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BEFORE YOU START

With a partner, discuss how using the land in the way shown in Figure B15.01 could affect the organisms that might otherwise live there.

Make a list of your ideas, and then share them with the rest of the class.

Figure B15.01: This field is being used to grow lettuce plants.

SCIENCE IN CONTEXT B15.01

Saving a species on the brink

Black-footed ferrets used to be common on the prairies of North America (Figure B15.02). But, as humans took over more and more land to graze cattle and grow crops, their habitat and food supply dwindled. Black-footed ferrets are predators that feed almost entirely on burrowing rodents called prairie dogs. Farmers killed large numbers of prairie dogs because they thought the rodents competed with cattle for grass. In 1974, the black-footed ferret was declared extinct in the wild.

Figure B15.02: Two black-footed ferrets.

But in 1981, in Wyoming, a dog brought a dead black-footed ferret to his owners. They notified wildlife officials, who leapt into action. Searches for the ferrets eventually discovered a small population of them living nearby.

The wild ferrets were given protection. But, as their numbers remained low, it was eventually decided that they needed more help. Some of the ferrets were taken to zoos, where they were given the right conditions to help them to breed. Many of the offspring were reintroduced into suitable habitats in several states, where their populations are gradually growing.

Today, the black-footed ferret is out of danger. Just in time, we managed to reverse a population decline that would have resulted in extinction.

Discussion questions

1 Do you think it is important for humans to try to prevent species from becoming extinct?

2 What are your reasons for your point of view?

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B15.01 Habitat destruction

Ecosystems and biodiversity

Look at Figure B15.03. This shows an **ecosystem**. The study of ecosystems such as this is called **ecology**. There are many words that you need to be able to use when you learn, talk and write about ecology. Some are introduced here.

The area where an organism lives is called its **habitat**.

Tadpoles will not be the only organisms living in the pond. There will be many other kinds of animals and plants making up the pond **community**. A community is all the populations of all the different species, living in the same habitat.

KEY WORDS

ecosystem: a unit containing all of the organisms in a community and their environment, interacting together.

ecology: the study of organisms in their environment.

habitat: the place where an organism lives.

community: all of the populations of all the different species in an ecosystem.

biodiversity: the number of different species that live in an area.

An ecosystem consists of the interactions between the living organisms in a pond, the water in it, the stones and the mud at the bottom. It is defined as the interactions between the organisms in a community and their environment. **Biodiversity** is a measure of the relative abundance of each of these species. The more species, and the more individuals in each species, the greater the biodiversity of an ecosystem.

As the human population continues to increase, we are affecting more and more ecosystems as we make places to live and for producing food. Our activities are having negative effects on ecosystems all over the world. In this topic, we will look at some of these effects. Topic B15.02 considers how we can conserve species, habitats and ecosystems, and why we should try to do this.

Reasons for habitat destruction

If humans destroy a habitat, then it is difficult for many species to survive in the new environment that results.

Habitats are destroyed when we use land for our own purposes. Here are some examples.

- We cut down native vegetation to make land available for growing crops, for farming livestock, for building houses and factories, and for building roads.

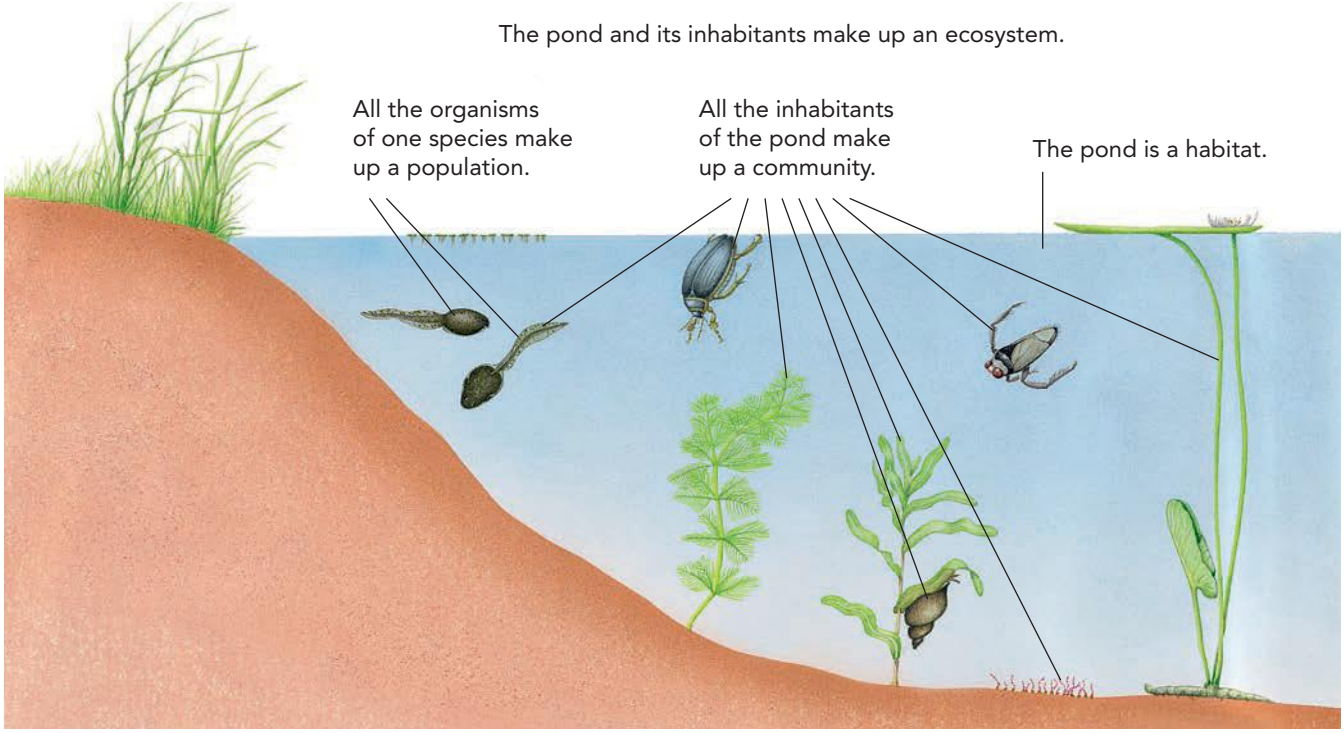

Figure B15.03: A pond and its inhabitants – an example of an ecosystem.

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- We damage habitats when we mine for natural resources, such as metal ores, building materials such as sand or gravel, or fossil fuels (Figure B15.04). The mine itself destroys the habitats by removing the soil and vegetation, and toxic run-off (water that flows away from the mine) can enter rivers or the soil in the surrounding area.
- We add pollutants to land and water, which can kill the plants that normally live there, and so change the habitat.

Figure B15.04: This huge open pit copper mine is in Chile, in South America.

Habitats can also be damaged if we remove key species from them. For example, collecting live corals from coral reefs damages the whole coral reef habitat. This endangers the hundreds of species of other animals that depend on corals (Figure B15.05). Corals contain tiny photosynthetic algae inside their bodies, which are the start of every food chain on the reef. This is an example of how, by damaging the food webs in a habitat, we can affect the habitats of all the plants and animals that live there.

Deforestation

Humans have always cut down trees. Wood is an excellent fuel and building material. The land on which trees grow can be used for growing crops for food, or to sell.
One thousand years ago, most of Europe was covered by forests. Now, most of them have been cut down. The cutting down of large numbers of trees is called deforestation (Figure B15.06). Deforestation on a huge scale has happened in many countries recently and is still continuing in many places.

Figure B15.05: All the organisms that live on this coral reef, in the Red Sea off the coast of Sudan, depend on the living coral animals to provide their habitat.

Figure B15.06: When rainforest is cut down and burnt, as here in Brazil, habitats are destroyed, large amounts of carbon dioxide are released and soil is eroded.

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Deforestation causes many undesirable effects, including:

- reducing biodiversity
- **extinction**
- loss of soil
- flooding
- increase of carbon dioxide in the atmosphere.

KEY WORD

extinction: the complete loss of a species from Earth.

How does deforestation cause these undesirable effects? Rainforests occur in temperate and tropical regions of the world. Recently, most concern about deforestation has been about the loss of tropical rainforests. In the tropics, the relatively high and constant temperatures, and high rainfall, provide perfect conditions for the growth of plants (Figure B15.07). A rainforest is a very special place, full of many different species of plants and animals. More different species live in a small area of rainforest than in an equivalent area of any other habitat in the world. Rainforest has a high biodiversity.

When an area of rainforest is cut down, the soil under the trees is exposed to the rain. The soil of a rainforest is very thin. It is quickly washed away once it loses its protective cover of plants, and the roots that help to bind it together. This soil erosion may make it very difficult for the forest to grow back again, even if the land is left alone. The soil can also be washed into rivers, filling them with soil so that the water overflows and causes flooding (Figures B15.08 and B15.09).

Figure B15.07: This rainforest is in the Royal Belum State Park in Malaysia, where it is protected from damage by humans.

Figure B15.08: The trees that used to cover this hillside were cut down so that people could grow crops. Instead, the rain is washing the unprotected soil down the hillside.

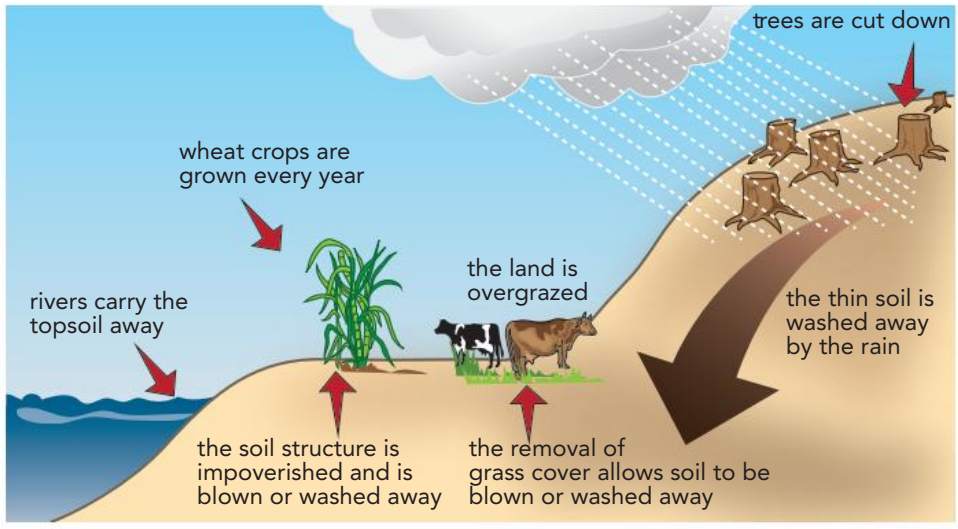

Figure B15.09: How human activities can increase soil erosion.

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The loss of part of a rainforest means a loss of a habitat for many different species of animals (Figure B15.10). Even if small 'islands' of forest are left as reserves, these may not be large enough to support a breeding population of the animals. Deforestation threatens many species of animals and plants with extinction.

Figure B15.10: Many animals, such as these macaws, cannot survive if deforestation destroys their habitat.

The loss of so many trees can also affect the water cycle, and the amount of rain that falls nearby. While trees are present and rain falls, a lot of it is taken up by the trees and transported into their leaves. It then evaporates, and goes back into the atmosphere in the process of transpiration. If the trees have gone, then the rain simply runs off the soil and into rivers. Much less goes back into the air as water vapour. The air becomes drier, and less rain falls. This can make it much more difficult for people to grow crops and keep livestock.

Most tropical rainforests grow in developing countries, and in some of these countries many of the people are very poor. The people may cut down the forests to clear land on which they can grow food. It is difficult to expect someone who is desperately trying to produce food to keep their family alive, not to clear land, unless you can offer some alternative. International conservation groups such as the World Wide Fund for Nature, and governments of the richer, developed countries can help. Money provided by these organisations can help to provide alternative sources of income for people. Many of the most successful projects involve helping local people to make use of the rainforest in a sustainable way.

In some countries, the greatest pressure on the rainforest may come from the country's own government, rather than the people living in or near the rainforest. For example, the government may be paid large amounts of money to allow logging companies to cut down forests and extract the timber.

Questions

B15.01 Explain why habitat destruction can lead to extinction of a species.

B15.02 Explain why habitats such as coral reefs and tropical rainforests have a much higher biodiversity than a field in which a single crop is grown.

B15.03 Outline *five* harmful effects of deforestation.

ACTIVITY B15.01

Deforestation poster

Work with a partner to produce a poster illustrating the causes and effects of deforestation.

You could use pictures downloaded and printed from the internet or you could draw your own pictures.

You could use the internet to find some specific examples, such as how habitats have been damaged by deforestation, how deforestation has led to flooding or how deforestation has reduced soil cover.

Try to achieve a good balance of illustration and text, to keep people's interest as they look at your poster, and so that they can learn useful information from it.

Peer assessment

Ask another pair to explain their poster to you.

How well do you think their poster achieves these criteria?

- It is interesting to look at, and grabs your attention.
- It contains information about both the causes and the effects of deforestation.
- There are some good examples provided, which are interesting and help to make a clear point.
- There is plenty of genuine scientific information, containing correct facts.

Reflection

How do you search for useful sources on the internet?

How do you decide whether you can trust the information on a particular website?

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B15.02 Conservation

Conservation is the process of looking after the natural environment. Conservation attempts to maintain or increase the biodiversity of an area (the range of different species living in an area). We have seen that one of the greatest threats to biodiversity is the loss of habitats. Each species of living organism is adapted to live in a particular habitat. If this habitat is destroyed, then the species may have nowhere else to live, and will become extinct.

Endangered species

A species that no longer has any living individuals on Earth is said to be extinct. A species whose numbers have fallen so low that it is at risk of becoming extinct is **endangered**. Once a species has become extinct, it is gone for ever. In Chapter B14, you explored how overharvesting and the introduction of foreign species into a habitat can cause native species to become endangered, and even extinct.

Through the history of life on Earth, millions of species have become extinct. Palaeontologists (people who study fossils) have identified several periods in the past when huge numbers of species seem to have become extinct. These are called mass extinction events (Figure B15.11).

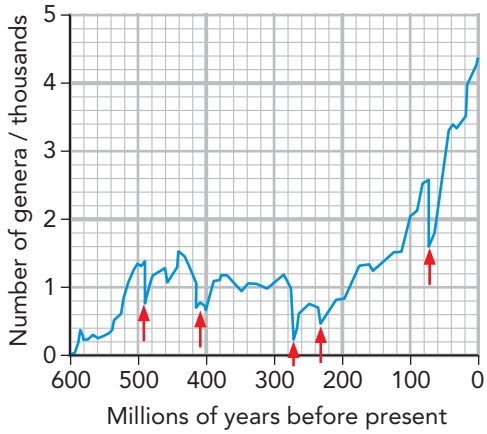

Figure B15.11: Mass extinction events have occurred five times in the last 500 million years.

KEY WORD

endangered: at serious risk of becoming extinct.

Each of these mass extinctions was caused by a major change in the conditions on Earth. The most catastrophic event occurred about 251 million years ago, when 96% of all species disappeared. We are not sure what caused this event, but major changes to the climate may have played a part. These might have been brought about by the continuous eruption of huge volcanoes in Siberia. It is also possible that an asteroid hit the Earth at this time.

Another major extinction event is happening now. This time, no asteroid is involved. The cause of the mass extinction is us.

Species can become extinct for many different reasons. These include:

- climate change, habitat destruction and pollution – which are all described in Topic B15.01
- hunting by humans – either for food or sport
- overharvesting – such as a species of fish or a species of tree
- introduction of new species to an ecosystem.

We have seen that the addition of extra carbon dioxide and methane to the atmosphere is causing climate change. As temperatures rise on Earth, organisms with adaptations that allow them to live in a particular environment may no longer be so well adapted. This is especially true of species that require cold conditions, such as polar bears. Polar bears need large areas of sea ice on which to hunt seals. As the ice caps melt, they may be left without a habitat.

Conserving endangered species

Understanding why a species can become endangered or extinct can help us to prevent this happening. For example, in the 1970s, the Mauritian green parakeet, also known as the echo parakeet, was said to be the most endangered bird species in the world (Figure B15.12). Only about ten birds were known to exist. These parakeets live in forests and scrub habitats, but by 1996 only 5% of Mauritius was still covered with its native vegetation. The parakeets, which feed on fruits of native trees, had little to eat. They were also threatened by introduced species such as rats and monkeys, which took eggs from nests and competed with the parakeets for food. And the loss of old trees meant that there were few suitable nest sites available.

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Figure B15.12: Mauritian green parakeets in their natural habitat.

In 1973, an intensive conservation programme began. At first, it concentrated on helping the parakeets to survive and breed in their habitat. Nest boxes were put up, predators were controlled, and non-native trees and weeds were cleared from the forest. This helped, but numbers still remained very low, so some of the eggs were taken to be reared in captivity. Many captive-reared birds have now been released into the wild. The population stood at over 700 birds in 2020, so it looks as though this parakeet is now out of immediate danger.

Many local organisations and individuals have been involved in this conservation project. Visits to schools and other education projects have helped to make young people aware of the importance of taking care of this endangered species, and how their actions can help it to survive.

This conservation success story illustrates many of the different tactics that can be used to conserve endangered species. They include:

- monitoring and protecting the species in its natural habitat
- using **captive breeding** programmes
- educating local people about the importance of conservation, and what they can do to help.

KEY WORDS

captive breeding: keeping animals in captivity (e.g. in a zoo) and allowing them to breed, in order to increase the numbers in the population.

Captive breeding and seed banks

Many zoos have captive breeding programmes. Animals are kept safe in the zoo, and encouraged to breed. This can build up the species' population. The hope is that some of the individuals can eventually be returned to the wild. However, this is only possible if the dangers that made them endangered in the first place – such as hunting or habitat destruction – can be reduced.

Animals are not the only organisms that are in danger of extinction. Many plant species are also under threat. We can use all of the same techniques that are used to conserve threatened animal species, but there is also another possibility: building up **seed banks** (Figure B15.13).

Figure B15.13: The Svalbard Seed Vault, in Norway, stores more than half a million different kinds of seeds deep under the frozen ground.

Seeds are often able to survive for many years in a dormant state, and then germinate when conditions are right. We can make use of that by collecting and storing seeds of as many different plant species as possible. These can be kept safe for long periods of time. In the future, if a species is threatened with extinction, we will have some of their seeds that can be used to grow into new plants, either to be kept 'in captivity' or reintroduced into their natural habitat.

Some of the seeds of each species are sown and allowed to grow into new plants from time to time. New seeds can then be collected, and stored. This makes sure that there are always seeds that have not been stored for too long, which could make them lose their ability to germinate.

KEY WORDS

seed bank: facility in which seeds of different plant species, or crop varieties, are stored for long periods of time, in order to conserve as many different species and varieties as possible.

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Many zoos, all over the world, are involved in captive breeding programmes for endangered species of animals. Zoos keep records of the pedigrees of their individual animals, and animals may be moved from one zoo to another so that males and females that are genetically different from one another can mate and produce offspring. This helps to maintain genetic diversity in the captive population. The aim is to be able to reintroduce some of the animals to the wild eventually, so that the wild population is increased. However, this can only work if the habitat for the animals is protected, so that whatever caused the species to become endangered in the first place is not repeated.

Animals in captivity do not always breed readily. Their unusual surroundings may not provide the correct environment for them to become ready to mate, or a particular male and a female may simply not respond to each other. This is often the case with giant pandas, for example. Males and females often show no interest in mating. In those cases, the zoo can help by using techniques called assisted reproduction. These include **artificial insemination (AI)** and **in vitro fertilisation (IVF)**.

AI involves taking semen from the male and inserting it into the vagina of the female. Hopefully, some of the sperm in the semen will find their way to an egg and fertilise it. The zygote will then develop into an embryo and implant into the uterus in the normal way.

Before AI is carried out, the female must be at the correct stage of her reproductive cycle, and there must be a good chance that there is an egg in her oviducts. In giant pandas, this happens only once a year, and the female only has an egg available for fertilisation for about 24 to 36 hours. She is monitored regularly, by testing the hormones in her urine, so that the perfect time for AI can be judged.

IVF is a little bit more difficult. It involves collecting eggs from the female, placing them in a sterile liquid in a sterile container (such as a Petri dish) and then adding semen from the male. Fertilisation happens in the dish ('in vitro' means 'in glass') and several zygotes are formed. Some of these then divide to form tiny embryos. One or more of the embryos is then placed in the female's uterus, with the hope that it will implant in the normal way, grow into a fetus and eventually be born successfully.

Generally, it is necessary to wait until a female ovulates naturally before eggs can be harvested. She also needs to be in the correct stage of her reproductive cycle before the embryos produced in vitro can be implanted. But sometimes the female or male – or both – can be treated with hormones that cause them to produce gametes. So far, it is proving difficult to achieve success with this in many species, largely because we still do not fully understand the hormonal control of reproductive cycles in most endangered species.

KEY WORDS

artificial insemination (AI): introducing semen, containing sperm, to the reproductive organs of a female; fertilisation occurs in her body in the normal way.

in vitro fertilisation (IVF): adding semen, containing sperm, to eggs in a container in a laboratory; fertilisation occurs in the container, and embryos can later be inserted into the body of a female.

Maintaining genetic diversity

Genetic diversity is important to a population. If there is variation between individuals, then the population as a whole has a better chance of surviving if they are threatened by a pathogen, or if their habitat changes in some way. At least some of the individuals may have variations that allow them to survive and reproduce, even if others are killed.

When the numbers of a species drop to very low levels, so that only a few individuals survive, then much of this genetic variation is lost. This makes the species much more likely to become extinct, especially if environmental conditions change.

Low levels of genetic variation also make it more likely that, when two individuals breed together, they may each carry the same harmful recessive allele of a gene. Some of their offspring may therefore inherit this harmful allele from each parent. As a result, they could have a homozygous recessive genotype which produces a phenotype making them less likely to survive.

This is a concern for the green parakeets in Mauritius. All the individuals now alive were bred from the ten birds that remained in the 1970s, so they are all quite closely related and share many of the same alleles. The breeding programmes are being organised to try to keep as much genetic diversity as possible.

Scientists at seed banks also work to maintain genetic diversity among the seeds that are stored. When seeds are collected from the wild, the collectors try to take them from different places, so that the plants that produced the seeds are not likely to be closely related. In the bank, some seeds are germinated every now and then, to produce fresh seeds for storage. When this is done, care can be taken to cross plants with different genotypes, to maintain genetic diversity among the seeds that are stored.

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Reasons for conservation programmes

So far, we have taken for granted that we want to try to stop species becoming extinct. But conservation programmes are expensive. They can cause conflict with people who want to use an area of land for a different purpose. So, what are the arguments for spending money and effort on trying to conserve endangered species and their habitats? Here are just a few of these arguments.

- For many of us, it is clear that we have no right to make any species extinct. We share the Earth with many different species and we have a responsibility to make sure that they can live successfully in their habitats. We are keeping them safe so that future generations can enjoy them.
- If we damage ecosystems, we can be doing harm to ourselves. Cutting down large numbers of trees, for example, can reduce the amount of water vapour that goes back into the air, which in turn can reduce rainfall. People who depend on locally collected wood for fuel may no longer be able to heat their homes or cook food.
- Losing species from an ecosystem, or introducing species that do not belong there, can have wide-reaching effects. The loss of one species may have harmful effects on other species that are part of the same food web, by reducing their food supplies. Conserving ecosystems can also help to maintain efficient recycling of nutrients such as nitrogen, through the nitrogen cycle.
- Many plant species contain chemicals that can be used as drugs. If we lose plant species, we may be losing potential new medicines.
- We have seen how selective breeding has been used to produce new varieties of crop plants. Wild relatives of our crop plants contain different alleles of genes that could be useful in future breeding programmes. Conserving wild plants, as well as all the different varieties of crop plants, is important if we are not to lose potentially useful alleles.

Questions

B15.04 List *five* reasons why species can become endangered or extinct.

B15.05 Explain why introducing a new species to an ecosystem can cause native species to become endangered.

B15.06 Describe what is meant by captive breeding and outline how it can help to save a species from extinction.

B15.07 Explain why it is important to try to maintain genetic diversity when a captive breeding programme is undertaken.

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PROJECT B15.01 A CONSERVATION SCENARIO

Conservation projects are often difficult to implement, because people may not always agree about the best thing to do.

Work in a group of five or six to write, produce and perform a short play involving a number of different people with differing viewpoints about a conservation project.

It is best if you use your own idea for a scenario. If you are stuck for ideas, here are three to start you off.

- A government wants to increase the tax on fuel, to reduce the use of cars and therefore reduce carbon dioxide emissions. Some people are strongly against the tax rise, because it will increase their costs and make it more difficult for them to travel for work or leisure.
- An international organisation proposes banning fishing in an area of the oceans, to allow fish stocks to recover. Fishermen from several countries, who normally fish in that area, strongly oppose the ban, because it will cause hardship for them and threaten the economy of the coastal towns where they live.
- A conservation organisation wants to kill predators that have been introduced to an island, where they are threatening native species with extinction. Some people are strongly opposed to this, because they like the introduced species (which happens to be cute and furry) and think it is cruel to kill them when the situation is not the fault of the introduced species.

Figure B15.14: Costa Rica is famous for its conservation efforts which have made it one of the most popular eco-tourism destinations in the world.

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SUMMARY

An ecosystem is a unit containing the community of organisms and their environment, interacting together.
Biodiversity is the number of different species that live in an area.
Farmers gain efficiency by growing crops as monocultures, allowing them to sow, tend and harvest a big area in the same way at the same time. However, monocultures are not good for ecosystems, as they greatly reduce biodiversity.
Habitats for species are destroyed through humans using land for growing food crops, farming livestock and housing; through using land to extract natural resources such as mineral ores and fossil fuels; and through the pollution of land, fresh water and the sea.
Deforestation causes habitat destruction, reduces biodiversity, causes extinction of species, increases the risk of soil erosion and flooding, and increases the carbon dioxide concentration in the air.
Climate change, habitat destruction, hunting, pollution and introduced species can put native species at risk of becoming extinct.
Monitoring and protecting species in the wild, and their habitats, as well as education, captive breeding programmes and seed banks, can help to conserve endangered species.
Conservation is important for: maintaining and increasing biodiversity; reducing extinction; protecting vulnerable environments; and maintaining ecosystem functions, including nutrient cycling, and provision of resources including food, drugs, fuel and genes for crop breeding.

PRACTICE QUESTIONS

1 **Identify** which of these activities does not increase the risk of extinction of species.

A captive breeding **B** climate change

C hunting **D** introducing non-native species **[1]**

2 Identify the correct description of artificial insemination (AI).

A adding sperm to eggs in a dish in a laboratory

B encouraging animals to breed in captivity

C inserting semen into the reproductive system of a female

D storing seeds in a seed bank **[1]**

3 **a** Rainforests have high biodiversity. **Define** *biodiversity*. **[1]**

b **Give** the name of the gas that trees remove from the air when they photosynthesise. **[1]**

c Deforestation causes habitat loss. **Suggest** what might happen to species of plants that are adapted to live in the rainforest if large areas of trees are cut down. **[1]**

d **State** what happens to the greenhouse effect when the concentration of carbon dioxide in the atmosphere increases. **[1]**

[Total: 4]

COMMAND WORDS

identify: name/select/recognise.

define: give precise meaning.

give: produce an answer from a given source or recall/memory.

suggest: apply knowledge and understanding to situations where there are a range of valid responses in order to make proposals/put forward considerations.

state: express in clear terms.

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CONTINUED

4 The hawksbill turtle has lost 90% of its population in the last 100 years. It is classified by the International Union for the Conservation of Nature (IUCN) as an endangered species. The photograph shows a hawksbill turtle.

a **Describe** what is meant by an endangered species. **[2]**

b Hawksbill turtles spend most of their lives at sea. The females become ready to breed when they are 30 years old. They come to sandy beaches to lay their eggs in nests that they dig in the sand. The young hatch after about 60 days. The tiny turtles burrow out of their nest and make their way down the beach to the sea.

Use this information to **deduce** why hawksbill turtles are endangered. **[3]**

[Total: 5]

5 The Iberian lynx, *Lynx pardinus*, is an endangered species. The photograph shows an Iberian lynx.

a The main reason that the Iberian lynx has become endangered is loss of habitat.

Suggest *two* reasons why the habitat of the Iberian lynx has been lost. **[2]**

COMMAND WORDS

describe: state the points of a topic/give characteristics and main features.

deduce: conclude from available information.

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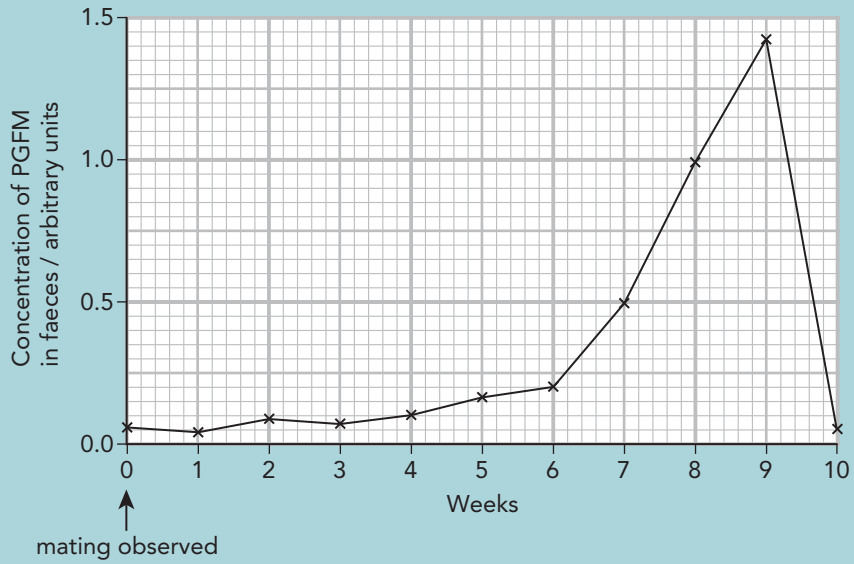
CONTINUED

b A captive breeding programme has been set up, to try to increase the numbers of this species. However, this has proved difficult because it is not easy to determine when a female lynx has become pregnant.

Researchers collected faeces from several individual female captive Iberian lynx, and measured the quantity of a chemical called PGFM. The results are shown in the graph.



i Suggest why it is helpful to be able to determine when a female lynx in a captive breeding programme has become pregnant. **[1]**

ii Use the graph to **explain** how monitoring PGFM levels in faeces can help researchers to determine when a female lynx is pregnant, and when she is likely to give birth. **[3]**

iii In the captive breeding programme, animals are often moved from one breeding institution to another. Explain how this can increase the likelihood of the programme being successful. **[3]**

[Total: 9]

6 Describe how seed banks can help to conserve endangered species. **[6]**

COMMAND WORD

explain: set out purposes or reasons/make the relationships between things clear/say why and/or how and support with relevant evidence.

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SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
explain the meanings of the terms *habitat*, *population*, *community* and *ecosystem*	B15.01			
describe biodiversity as the number of different species that live in an area	B15.01			
describe the reasons for habitat destruction, including increased area for food crop growth, livestock production, livestock housing, extraction of natural resources, pollution (freshwater and marine)	B15.01			
explain how humans can have a negative impact on habitats by altering food webs	B15.01			
explain the undesirable effects of deforestation: habitat destruction, reducing biodiversity, extinction, loss of soil, increased flooding, increase of carbon dioxide in the atmosphere	B15.01			
explain that climate change, habitat destruction, hunting, pollution and introduced species can cause species to become endangered or extinct	B15.02			
describe how monitoring and protecting species and habitats, education, captive breeding programmes and seed banks can help to conserve endangered species	B15.02			
describe maintaining or increasing biodiversity, reducing extinction, maintaining nutrient cycling and the provision of resources such as food, drugs, fuel and genes, as reasons for conservation programmes	B15.02			
describe the use of AI and IVF in captive breeding programmes	B15.02			
explain why a decrease in population size of a species can lead to loss of genetic diversity, and why this increases the risk of extinction.	B15.02			

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C1

States of matter

All learners study some content in this chapter

IN THIS CHAPTER YOU WILL:

- learn that matter can exist in three different states: solid, liquid or gas
- understand that substances can change state depending on the physical conditions
- understand that matter is made up of very small particles such as atoms or molecules
- learn how to describe the structure of the physical states in terms of the arrangement and movement of particles
- describe how changes in temperature and pressure affect the volume of a gas
- explain diffusion in terms of the kinetic particle theory
- think about how the movement of particles (kinetic particle theory) helps explain how changes of state happen
- understand the effects of changes in temperature and pressure on the volume of a gas
- learn how the molecular mass of particles in a gas affects the rate of diffusion.

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BEFORE YOU START

You will know about solids, liquids and gases from general life experience and your science courses. However, the ideas concerning the ways in which one state of matter changes into another are more complex.

Think about water heating in a pan. Bubbles form in the water and water vapour is formed above the pan. If the same pan of water is then placed in a freezer, solid ice will form. What is happening to the water molecules? How are they behaving differently in each of these forms?

Spray a small amount of air freshener at the front of a room. How does the smell spread around the room? Shake the can. Can you hear the liquid in it? Or try placing some liquid perfume in a dish in front of you and see how long it takes for someone to notice the scent some distance away.

Discuss these observations in terms of changes of state and the movement of the molecules involved.

Look at the flowchart (Figure C1.01). Working in groups, can you add more detail to improve and extend the flowchart?

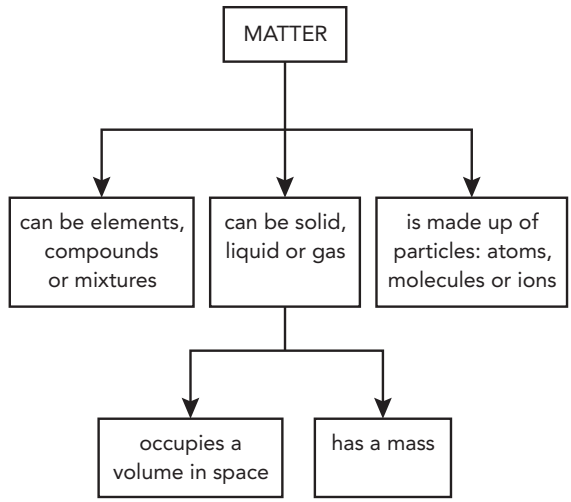

Figure C1.01: Flowchart of the nature of matter.

SCIENCE IN CONTEXT C1.01

Lord of the rings

Saturn is perhaps the most beautiful of the planets of our solar system. Saturn has fascinated astronomers, even the famous Galileo, because of its mysterious rings. Galileo himself was confused by the rings. At first, he thought that the rings were planets. The *Pioneer*, *Voyager* and *Cassini-Huygens* space probes have sent back a lot of information to Earth about the structure of the moons and rings of Saturn. Figure C1.02 is an image captured by the Hubble Space Telescope.

Each ring around Saturn is made up of a stream of icy particles. They follow each other nose-to-tail, like cars in a traffic jam, around the planet. The particles can be of widely varying sizes. The rings resemble a snowstorm, in which tiny snowflakes are mixed with snowballs that can be as large as a house. The ice that surrounds one of the most spectacular planets of our solar system is made of water, which is the same substance (with the same chemical formula, H_2O) that covers so much of the Earth's surface.

Figure C1.02 also shows the pastel colours of the clouds of ammonia and methane in Saturn's atmosphere. However, the bulk of the planet is made of hydrogen and helium gases. Deep in the centre of these lightweight gases is a small rocky core, surrounded by a liquid layer of the gases. The hydrogen is liquid because of the high pressure in the inner regions of the planet nearest the core. The liquid hydrogen shows metallic properties, which produces the planet's magnetic field. A study of Saturn's physical structure emphasises how substances that we know on Earth can exist in unusual physical states in different environments.

Figure C1.02: Saturn and its rings. A photograph taken by the Hubble Space Telescope.

Discussion questions

1 Why are the planets Jupiter and Saturn called 'gas giants'? What progression do we see in the physical nature of the planets as we move away from the Sun?

2 Why does hydrogen only exist as a liquid under such extreme conditions of temperature and pressure?

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C1.01 Solids, liquids and gases

There are many different kinds of **matter**. The word is used to cover all the substances and materials of which the universe is composed. Samples of all of these materials have two properties in common: they each occupy space (they have volume) and they have mass.

Chemistry is the study of how matter behaves, and of how one kind of substance can be changed into another. Whichever chemical substance we study, we find that the substance can exist in three different forms (or physical states) depending on the conditions. These three different **states of matter** are known as solid, liquid and gas.

KEY WORDS

matter: anything that occupies space and has mass.

states of matter: solid, liquid and gas are the three states of matter in which any substance can exist, depending on the conditions of temperature and pressure.

Changing the temperature and/or pressure can change the state in which a substance exists (Figure C1.03).

Each of the different physical states has certain general characteristics that are true whatever chemical substance is being considered. Table C1.01 highlights a major difference between solids and the other two physical states. Liquids and gases are able to flow, but a solid has a fixed shape and volume. Liquids and gases are **fluids**. This means that liquids and gases can be poured, or pumped, from one container to another. The three physical states also show differences in the way they respond to changes in temperature and pressure. All three show an increase in volume (an expansion) when the temperature is increased and a decrease in volume (a contraction) when the temperature is lowered. The effect is much bigger for a gas than for a solid or a liquid.

KEY WORD

fluid: a gas or a liquid; fluids are able to flow.

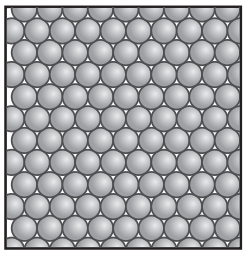
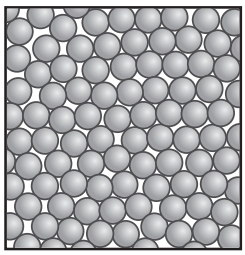
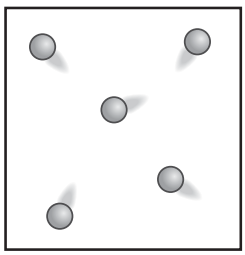
Physical state	Particle diagram	Particle separation, arrangement and motion	Volume	Density	Shape	Fluidity
solid		• packed close together • in a regular arrangement or lattice • not able to move freely, but simply vibrate in their fixed positions.	has a fixed volume	high	has a definite shape	does not flow
liquid		• closely packed together • in an irregular arrangement • able to move around past each other.	has a fixed volume	moderate to high	no definite shape – takes the shape of the container	generally flows easily
gas		• arranged totally irregularly • spread very far apart compared to solids and liquids • able to move randomly.	no fixed volume – expands to fill the container	low	no definite shape – takes the shape of the container	flows easily

Table C1.01: Differences in the properties of the three states of matter.

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Figure C1.03: Gallium metal melts with the warmth of the hand.

The volume of a gas at a fixed temperature can easily be reduced by increasing the pressure on the gas. Gases are easily compressed ('squashed'). Liquids are only slightly compressible, and the volume of a solid is unaffected by changing the pressure.

Changes in state

Large increases, or decreases, in temperature and pressure can cause changes that are more dramatic than expansion or contraction. They can cause a substance to change its physical state. The changes between the three states of matter are shown in Figure C1.04.

Melting and freezing

The temperature at which a substance turns to a liquid is called the **melting point (m.p.)**. This always happens at one particular temperature for each substance (Figure C1.05). The process is reversed at precisely the same temperature if a liquid is cooled down. It is then called the *freezing point* (f.p.). The melting point and freezing point of any given substance are both the same temperature. For example, the melting and freezing of pure water take place at 0 °C.

KEY WORDS

melting point (m.p.): the temperature at which a solid turns into a liquid – it has the same value as the freezing point; a pure substance has a sharp melting point.

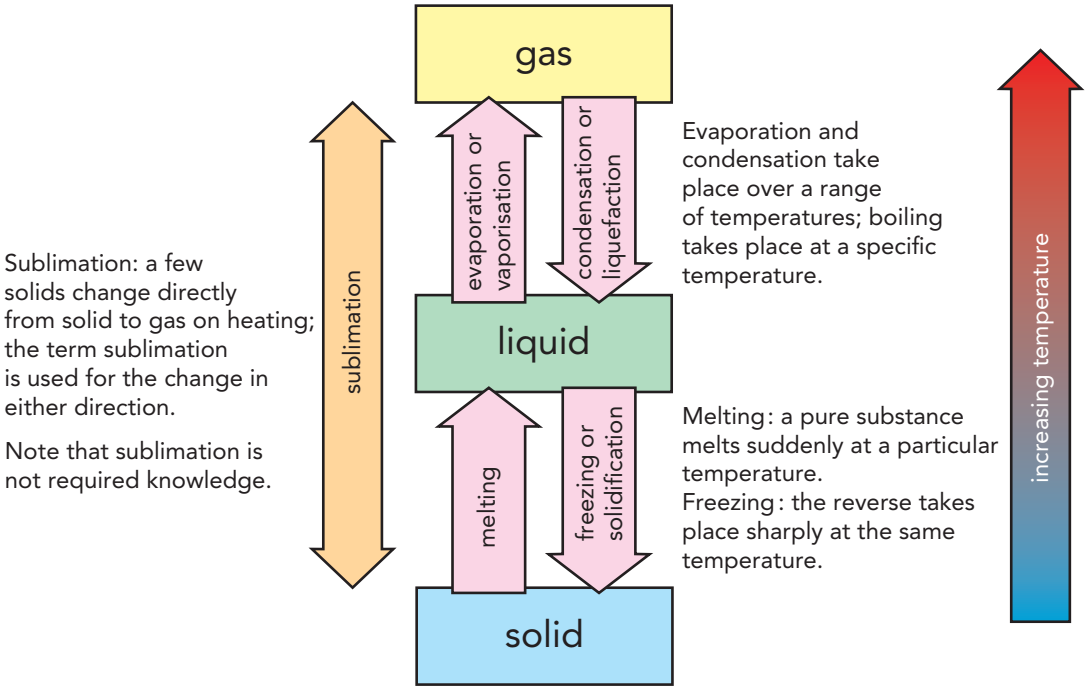

Figure C1.04: Changes of physical state and the effect of increasing temperature at atmospheric pressure.

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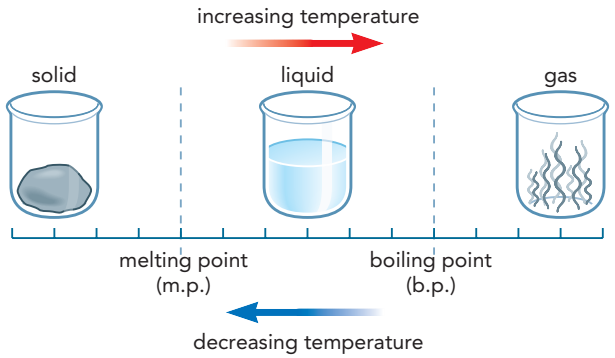

Figure C1.05: Relationship between the melting and boiling points of a substance.

Evaporation, boiling and condensation

If a liquid is left with its surface exposed to the air, it evaporates. When liquids change into gases in this way, the process is called **evaporation**. Evaporation takes place from the surface of the liquid. The larger the surface area, the faster the liquid evaporates. The warmer the liquid is, the faster it evaporates.

Eventually, at a certain temperature, a liquid becomes hot enough for gas to form within the liquid and not just at the surface. Bubbles of gas appear inside the liquid (Figure C1.06). This process is known as **boiling**. It takes place at a specific temperature for each pure liquid. This temperature is known as the **boiling point**.

Water evaporates fairly easily and has a relatively low boiling point (100 °C). Water is quite a **volatile** liquid. Ethanol, with a boiling point of 78 °C, is even more volatile than water. It has a higher **volatility** than water and evaporates more easily.

Figure C1.06 a: Water boiling in a glass kettle; bubbles are formed throughout the liquid. **b:** A boiling kettle produces colourless, invisible water vapour that then condenses to produce a cloud of steam.

The reverse of evaporation is **condensation**. This is usually brought about by cooling. However, as we saw earlier, the gas state is the one most affected by changes in pressure. It is also possible, at normal temperatures, to condense a gas into a liquid by increasing the pressure, without cooling.

KEY WORDS

evaporation: a process occurring at the surface of a liquid, involving the change of state from a liquid into a vapour at a temperature below the boiling point.

boiling: the process of change from liquid to gas at the boiling point of the substance; a condition under which gas bubbles are able to form within a liquid – gas molecules escape from the body of a liquid, not just from its surface.

boiling point: the temperature at which a liquid boils, when the pressure of the gas created above the liquid equals atmospheric pressure.

volatile: term that describes a liquid that evaporates easily; it is a liquid with a low boiling point because there are only weak intermolecular forces between the molecules in the liquid.

volatility: the property of how easily a liquid evaporates.

condensation: the change of a vapour or a gas into a liquid; during this process heat is given out to the surroundings.

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We can see these different processes in action if we look closely at a kettle as water boils (Figure C1.06b). Colourless, invisible water vapour escapes from the kettle. Water vapour is present in the clear region we can see at the mouth of the kettle. The visible cloud of steam is made up of droplets of liquid water formed by condensation as the vapour cools in the air.

The boiling point of a liquid can change if the surrounding pressure changes. The value given for the boiling point is usually stated at the pressure of the atmosphere at sea level (*atmospheric pressure* or *standard pressure*). If the surrounding pressure falls, the boiling point falls. The boiling point of water at standard pressure is 100 °C. On a high mountain, the boiling point is lower than 100 °C. If the surrounding pressure is increased, the boiling point rises.

Pure substances

A **pure substance** consists of only one substance without any contaminating impurities. A pure substance melts and boils at definite temperatures. The values for the melting point and boiling point of a pure substance are precise and predictable (see Chapter C12).

Impurities often affect the value of the melting or boiling point of a substance. An impure substance sometimes melts or boils over a *range* of temperatures, not at the precise point of the pure substance.

This means that we can use melting and boiling points to test the purity of a sample. These values can also be used to check the identity of an unknown substance (see Chapter C12 for the method).

KEY WORDS

pure substance: a single chemical element or compound; it melts and boils at definite precise temperatures.

lattice: a regular three-dimensional arrangement of atoms, molecules or ions in a crystalline solid.

Questions

C1.01 State the names for the following physical changes:

- **a** liquid to solid
- **b** liquid to gas at a precise temperature
- **c** gas to liquid.

C1.02 The melting and boiling points of three pure substances are given in Table C1.02.

Substance	Melting point / °C	Boiling point / °C
ethanol	−117	78
methane	−182	−164
mercury	−30	357

Table C1.02: Melting and boiling points of ethanol, methane and mercury.

- **a** All three substances have negative values for their melting point. Which of them has the lowest melting point?
- **b** Which *two* substances are liquids at room temperature? Explain your answer.
- **c** What effect does the presence of an impurity have on the freezing point of a liquid?

C1.03

- **a** What do you understand by the word *volatile* when used in chemistry?
- **b** Put these three liquids in order of volatility, with the most volatile first: water (b.p. 100 °C), ethanoic acid (b.p. 128 °C) and ethanol (b.p. 78 °C).
- **c** Table C1.03 shows the melting and boiling points of four substances A–D. In which of these four substances are the particles arranged in a **lattice** (a regular structure) at room temperature?

Substance	Melting point / °C	Boiling point / °C
A	−115	79
B	80	218
C	−91	−88
D	−23	77

Table C1.03: Melting and boiling points of four unknown substances.

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C1.04 Iodine is often seen as an example of a substance that changes directly from a solid to a gas. However, data books that give the standard physical measurements for substances show values for the melting point (114 °C) and boiling point (184 °C) of iodine at atmospheric pressure.

a Explain why iodine seems to miss out the liquid stage if crystals are heated strongly in a boiling tube.

b Suggest how you could demonstrate that iodine can melt to form a liquid at atmospheric pressure.

Effects of temperature and pressure on the volume of a gas

The fact that the space between the rapidly moving particles in a gas is much greater than in the other two states of matter explains why the volume of a gas is much more easily changed by conditions of temperature and pressure. If the temperature is raised, then the gas particles move faster and there is less chance of interaction between them. The gas particles move faster and more freely and occupy a greater volume.

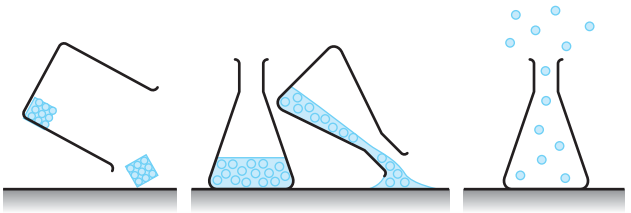
The opposite is true if the temperature is lowered. The particles move more slowly and occupy a smaller volume. Changes in pressure also affect the volume of a gas sample. An increase in pressure pushes the particles closer together. This means that the moving particles are more likely to interact with each other and move closer together. The opposite is true when the external pressure is lowered. The particles occupy a greater space and interactions between the particles are less likely.

Kinetic particle theory of matter

The idea that all substances consist of very small particles, **atoms**, allows us to explain the structure of the three different states of matter. The different levels of freedom of movement of the particles explains some of the different features of the three states. Figure C1.07 illustrates the basic features of the three states we discussed earlier (see Table C1.01).

The **kinetic particle theory** of matter describes the three different states, and the changes between them, in terms of the movement of particles. The major points of the theory are:

- All matter is made up of very small particles (different substances contain different types of particles, such as atoms, **molecules** or ions).
- Particles are moving all the time (the higher the temperature, the higher the average energy of the particles).



A solid cannot flow. It has a definite shape and volume.

A liquid can flow; it is a fluid. It has a definite volume but takes the shape of its container.

A gas is a fluid and spreads throughout its container. It has no definite volume.

Figure C1.07: The basic differences between the physical properties of the three states of matter.

- The freedom of movement and the arrangement of the particles is different for the three states of matter.
- The pressure of a gas is produced by the atoms or molecules of the gas hitting the walls of the container. The more often the particles collide with the walls, the greater the pressure.

Figure C1.08 is a more detailed summary of the organisation of the particles in the three states of matter and explains the changes involved in the different changes in state.

The highly structured, ordered microscopic arrangements in solids can produce the regular crystal structures seen in this state. In a solid, the particles are packed close together. The particles cannot move freely. They simply vibrate about fixed positions in their regular arrangement (lattice).

In a liquid, the particles are still close together. However, they can now move about past each other. The separation between particles is much greater in a gas. In a gas, the particles are very far apart and move randomly.

KEY WORDS

atom: the smallest particle of an element that can take part in a chemical reaction.

kinetic particle theory: a theory which accounts for the bulk properties of the different states of matter in terms of the movement of particles (atoms or molecules); the theory explains what happens during changes in physical state.

molecule: a group of atoms held together by covalent bonds.

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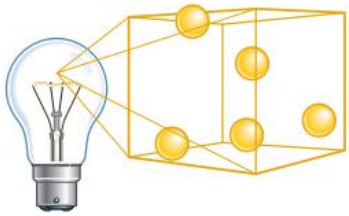
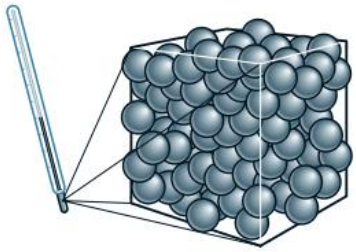


Gas
The particles in a gas are:
- arranged totally irregularly
- spread very far apart compared to solids and liquids
- able to move randomly.

On heating, the particles move faster and the liquid expands. In the liquid, some particles have enough energy to escape from the surface – evaporation takes place. As the temperature rises, more particles have enough energy to escape – evaporation is faster at higher temperatures. At the boiling point, the particles have enough energy to break the forces attracting them together – the particles move very fast and separate from each other – the liquid boils.

evaporation and boiling

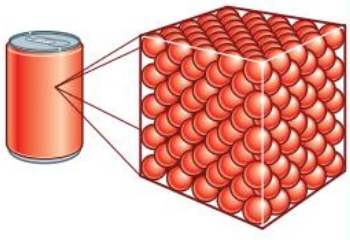


Liquid
The particles in a liquid are:
- closely packed together
- in an irregular arrangement
- able to move around past each other.

When the temperature is raised, the particles gain energy and vibrate more strongly; the particles occupy more space – this causes the solid to expand.

Eventually the particles have enough energy to break the forces holding the lattice together, and they can move around – the solid melts.

melting



Solid
The particles in a solid are:
- packed close together
- in a regular arrangement or lattice
- not able to move freely, but simply vibrate in their fixed positions.

Figure C1.08: Applying the kinetic particle theory to changes in physical state.

The ability of the particles to move in the liquid and gas phases produces their fluid properties. The particles are very widely separated in a gas, but close together in a liquid or solid. The space between the particles is called the **intermolecular space**.

In a gas, the intermolecular space is large and can be reduced by increasing the external pressure. Therefore, gases are easily compressible. In liquids, this space is very much smaller. As a result, liquids are not very compressible.

Changing the external pressure on a sample of a gas produces a change in volume that can easily be seen.

- An increase in external pressure produces a decrease in volume. The gas is compressed.
- A decrease in external pressure produces an increase in volume. The gas expands.

The volume of a gas is also altered by changes in temperature.

- An increase in the temperature of a gas produces an increase in volume. The gas expands.
- A decrease in temperature produces a contraction of the volume of a gas.

The movement of particles in a liquid also helps to explain evaporation from the surface of a liquid. Some of the particles are moving faster than other particles. At the surface, these faster moving particles may have enough energy to escape into the gaseous state (Figure C1.09).

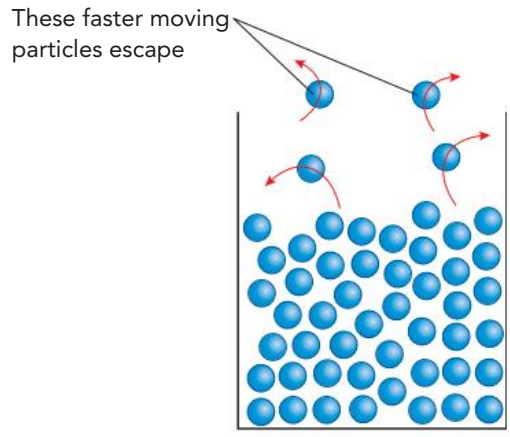


Figure C1.09: Faster moving particles leaving the surface of a liquid, causing evaporation.

KEY WORDS

intermolecular space: the space between atoms or molecules in a liquid or gas. The intermolecular space is small in a liquid, but relatively very large in a gas.

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Heating and cooling curves

When a solid is heated, the temperature rises until the solid starts to melt. However, close observation shows that the temperature stays constant during melting, until all the solid has melted. The temperature then rises as the liquid warms further. It is possible to continue to heat the liquid in the same apparatus until its boiling point is reached. Again, once evaporation has begun, the temperature stays the same until all the liquid has completely evaporated.

We can perform this experiment in reverse, producing a cooling curve (Figure C1.10). The level (horizontal) part of the curve occurs where the liquid freezes, forming the solid.

These experiments show that heat energy is needed to change a solid into a liquid, or a liquid into a gas. During the reverse processes, heat energy is given out.

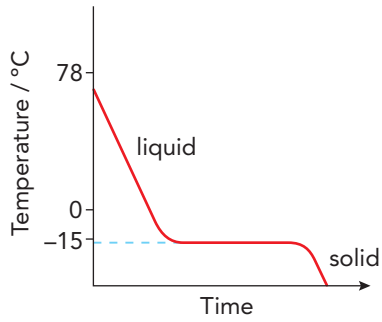

Figure C1.10: A cooling curve. The temperature stays constant while the liquid solidifies. A cooling mixture of ice and salt could be used to lower the temperature below 0 °C.

EXPERIMENTAL SKILLS C1.01

Plotting a cooling curve

In this experiment, you are going to plot cooling curves for two substances, A and B. This experiment investigates the energy changes taking place as a liquid cools down below its freezing point.

You will need:

- two beakers (250 cm^3)
- Bunsen burner
- tripod
- gauze
- heat-resistant mat
- stopwatch, stopclock or other timer
- two boiling tubes labelled A and B
- two stirring thermometers (−10 to 110 °C).

Substance A is paraffin wax (choose a low m.p. type, m.p. around 55 °C). Substance B is either octadecanoic acid (stearic acid) m.p. 70 °C or phenyl salicylate (salol) m.p. 43 °C.

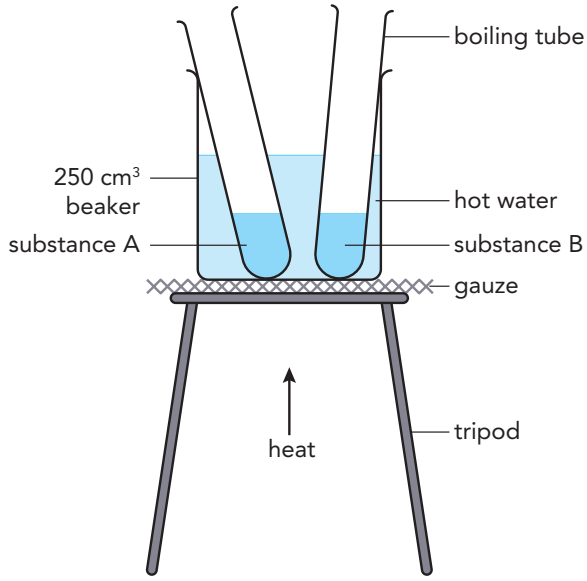

Figure C1.11: Samples A and B are melted in a water-bath.

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CONTINUED: C1.01

Safety

It is important that you follow the safety rules set out by your teacher for all practicals. In particular, pay attention to the type of Bunsen burner flame needed as well as the concentrations and volumes of chemicals used. Wear eye protection throughout.

Getting started

Before you start the experiment, make sure you are familiar with the scale on the thermometer you are using. You will need to be able to read it confidently. You can check on your reading of the thermometer as you are heating up the water-bath.

Make sure you and your partner are clear about the tasks you each have.

Method

1 Fill a 250 cm^3 beaker three-quarters full of water. Heat the beaker, using a Bunsen burner, to make a water-bath. Place a thermometer in the water. Heat the water until it is at 90 °C.

2 Put boiling tubes containing a sample of each solid A and B into the water-bath (Figure C1.11).

3 When the solid has melted, place a thermometer in each tube. There should be enough liquid to cover the bulb at the base of the thermometer.

4 Remove the tubes from the water-bath and stand them in an empty beaker for support.

5 Look at the thermometer and record the temperature in each tube. Then start the timer.

6 Look at the thermometer and record the temperature in each tube every minute until the temperature reaches 40 °C.

7 Plot a graph for each set of readings with time on the x-axis and temperature on the y-axis.

Questions

1 Which of the two substances is a pure substance? Explain your answer.

2 Explain any ways in which your method could be improved to give more reliable results.

Self assessment

Complete the self assessment checklist below to assess your graph drawing skills. For each point, award yourself:

2 marks if you did it really well

1 mark if you made a good attempt at it and partly succeeded

0 marks if you did not try to do it, or did not succeed

Checkpoint	Marks awarded
Have you drawn the axes with a ruler, using most of the width and height of the grid?	
Have you used a good scale for the *x*-axis and the *y*-axis, going up in 0.25 s, 0.5 s, 1 s or 2 s? (Note that the axes do not necessarily need to start at the origin (0, 0).)	
Have you labelled the axes correctly, giving the correct units for the scales on both axes?	
Have you plotted each point precisely and correctly?	
Have you used a small, neat cross or encircled dot for each point?	
Have you drawn a single, clear best-fit line through each set of points?	
Have you ignored any anomalous results when drawing the line through each set of points?	
Total (out of 14):	

Your total score will reflect how clear and well-presented your graph is. Drawing graphs is an important skill in chemistry as you need to be able to deduce reliable information from your graph.

Take a look at where you gave yourself 2 marks and where you gave yourself fewer than 2 marks. What did you do well, and what aspects will you focus on next time? When you have thought about your assessment, talk it through with your teacher to gain further advice on areas that would help you improve your presentation of graphical data.

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Questions

C1.05 Energy is needed to overcome the forces of attraction holding the particles in position in a solid. Energy is absorbed during melting. Figure C1.12 shows how energy is involved in the different changes of state. Copy and complete Figure C1.12 by providing labels for the positions A, B and C.

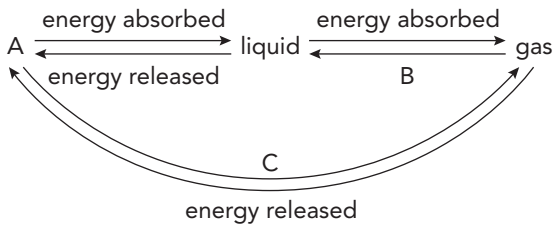

Figure C1.12: Energy changes involved in different changes of state.

C1.06 As an alternative to following the cooling of a substance, it is possible to draw a heating curve. Figure C1.13 shows the heating curve for substance X.

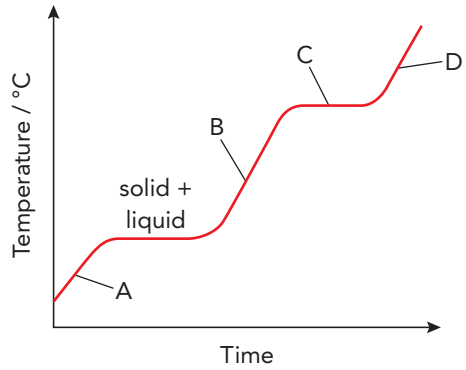

Figure C1.13: Heating curve for substance X.

What physical state, or states, will X be in at points A, B, C and D on the curve?

The interpretation of a cooling curve

We can use kinetic particle theory to explain a heating or cooling curve like the one in Figure C1.14.

In region A (Figure C1.14), the temperature is falling. The energy of the particles decreases. The particles move more slowly and interact with each other more strongly. The particles begin to come together to form the liquid. As the **intermolecular forces** increase between the particles, energy is given out. This results in the temperature staying constant until the gas is completely condensed to liquid.

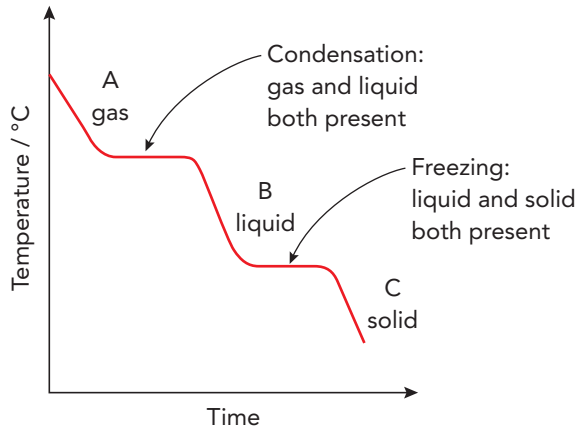

Figure C1.14: The energy changes taking place during the cooling of a gas to a solid.

Once the liquid is formed, the temperature starts to fall again (region B). The liquid cools. The particles in the liquid slow down and eventually the solid begins to form. The forces holding the solid together form and energy is given out. While the solid is forming, this release of energy keeps the temperature constant. The temperature stays the same until freezing is complete.

After the solid has formed, the temperature falls again (region C). The particles in the solid vibrate less strongly as the temperature falls.

The key points about the processes taking place during condensation and freezing are:

- as the particles come closer together, new forces of interaction take place
- this means that energy is given out during these changes
- therefore, the temperature remains unchanged until the liquid or solid is totally formed.

As energy is given out during these changes, condensation and freezing are **exothermic changes** (Chapter C5).

KEY WORDS

intermolecular forces: the weak attractive forces that act between molecules.

exothermic changes: a process or chemical reaction in which heat energy is produced and released to the surroundings; ΔH for an exothermic change has a negative value.

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On heating, the temperature stays constant during melting and boiling. At these stages, energy has to be put in to overcome the forces between the particles. The energy put in breaks these interactions. This allows the particles to move more freely and faster. As energy has to be put in during these changes, melting, evaporation and boiling are **endothermic changes** (Chapter C5).

KEY WORDS

endothermic changes: a process or chemical reaction that takes in heat from the surroundings; ΔH for an endothermic change has a positive value.

C1.02 Diffusion

Some of the earliest evidence for the kinetic model of the states of matter came from observations on **diffusion**, where particles spread to fill the space available to them.

The main ideas involved in diffusion are:

- Particles move from a region of higher concentration towards a region of lower concentration; eventually, the particles are evenly spread. Their concentration is the same throughout.
- The rate of diffusion in liquids is much slower than in gases.
- Diffusion does not take place in solids because the particles cannot move from place to place.

Figure C1.15: The diffusion of potassium manganate(VII) in water.

A potassium manganate(VII) crystal is placed at the bottom of a dish of water. The dish is then left to stand. At first the water around the crystal becomes purple as the solid dissolves (Figure C1.15). Particles move off from the surface of the crystal into the water. After some time, the crystal dissolves completely and the purple colour diffuses (spreads) through the liquid. Eventually, the whole solution becomes purple as the particles from the solid become evenly spread through the water.

Diffusion in solution is also important when the substance in solution is a gas. This is especially important in breathing. Diffusion contributes to the movement of oxygen from the lungs to the blood, and of carbon dioxide from the blood to the lungs.

KEY WORD

diffusion: the process by which different fluids mix as a result of the random motions of their particles.

Diffusion of gases

A few drops of liquid bromine are put into a gas jar and the lid is replaced. The liquid bromine evaporates easily. Liquid bromine is highly volatile. After a short time, the brown gas begins to spread throughout the jar. The jar becomes full of brown gas. Bromine vaporises easily and its gas will completely fill the container (Figure C1.16). Gases diffuse to fill all the space available to them. Diffusion is important for our 'sensing' of the world around us. It is the way that smells reach us.

The atoms or molecules in gases move at high speeds. We are being bombarded constantly by nitrogen and oxygen molecules in the air, which are travelling at about 1800 km/h. However, these particles collide very frequently with other particles in the air (many millions of collisions per second), so their path is not direct. These frequent collisions slow down the overall rate of diffusion from one place to another.

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Figure C1.16: Bromine vapour diffuses throughout the container to fill the space available.

Mass and diffusion

Not all particles diffuse at the same rate. The speed at which particles diffuse depends on the mass of the particles involved. At the same temperature, molecules that have a lower mass move, on average, faster than those with a higher mass. This is shown by the experiment in Figure C1.17. The ammonia and hydrochloric acid fumes react when they meet, producing a white smoke ring of ammonium chloride. This smoke ring is made of fine particles of solid ammonium chloride. The fact that the ring is not formed halfway along the tube shows that ammonia, the lighter molecule of the two, diffuses faster.

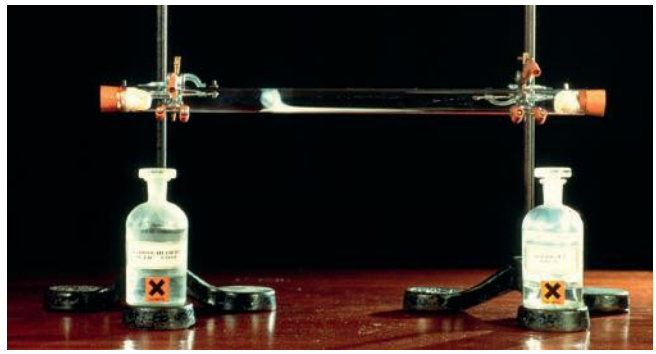

Figure C1.17: Ammonia and hydrochloric acid fumes diffuse at different rates. Ammonia is on the right, hydrochloric acid on the left.

The important points derived from the kinetic particle theory relevant here are:

- Heavier gas particles move more slowly than lighter particles at the same temperature.
- Larger molecules, therefore, diffuse more slowly than smaller ones.
- The rate of diffusion is inversely related to the mass of the particles.
- The average speed of the particles increases with an increase in temperature.

EXPERIMENTAL SKILLS C1.02

Investigating diffusion in liquids

This experiment demonstrates the process of diffusion in a liquid. Diffusion is shown by the formation of an insoluble precipitate where the ions meet in a solution.

You will need:

- Petri dish
- test-tube
- tweezers
- white tile
- silver nitrate, one crystal
- silver nitrate (aq)
- potassium iodide, one crystal
- potassium iodide (aq)
- distilled or deionised water.

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CONTINUED: C1.02

Safety

Wear eye protection throughout. Use tweezers to handle the crystals. Be careful with chemicals. Never ingest them and always wash your hands after handling them. Note that silver nitrate is corrosive, oxidising and can stain the skin. Silver nitrate is also hazardous to the aquatic environment. Waste silver nitrate solution must not be poured down the drain.

Getting started

Before you start, try the reaction between potassium iodide and silver nitrate solutions in a test-tube. Add 1 cm^3 of aqueous silver nitrate to a similar volume of potassium iodide solution. Note the formation of the precipitate, particularly its colour.

Method

1. Put a Petri dish on a white tile or piece of white paper. Fill the Petri dish nearly to the top with deionised water.
2. Using tweezers, put a crystal of silver nitrate at one side of the dish and a crystal of potassium iodide at the other side (Figure C1.18).
3. Look at the crystals. Notice that as the crystals begin to dissolve in the water, a new compound is formed within the solution.

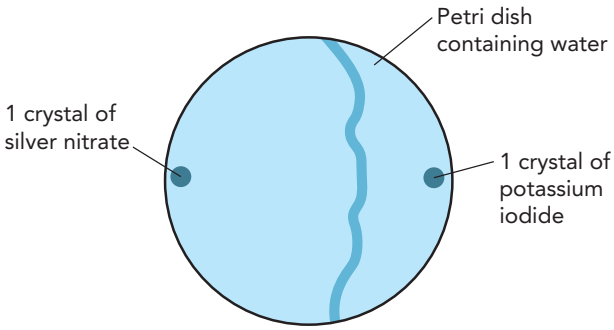

Figure C1.18: Experiment to investigate diffusion through water.

Questions

1. What is the precipitate formed in this reaction?
2. Write a word equation to show the reaction taking place.
3. What factors control where the solid is formed in the Petri dish?
4. Why does the solid not form exactly in the middle of the dish?

Questions

C1.07 A small amount of liquid bromine is placed in a gas jar, which is then sealed with a lid. Evaporation of the liquid bromine takes place.

$$Br_2(l) \rightarrow Br_2(g)$$

Use the ideas of the kinetic theory to explain why, after about an hour, the gaseous bromine molecules have spread to evenly occupy the whole container.

C1.08 A teacher carried out a class demonstration on diffusion similar to the one using ammonia ($M_r = 17$) and hydrochloric acid ($M_r = 36.5$) (Figure C1.19). However, they replaced the ammonia with methylamine ($M_r = 31$), which reacts in a similar way to ammonia (note that M_r is the relative molecular mass of the substance).

a Where would you predict the position of the smoke ring to be in this experiment? Explain your answer.

b Suggest other gases similar to hydrochloric acid that could replace it in this demonstration (use textbooks or the internet to find a possible acid).

C1.09 Experiments comparing the rate of diffusion of different gases can be done using the apparatus shown in Figure C1.19.

A cylinder made of **porous pot** is used. Gas molecules are able to pass through this cylinder. Any change in pressure in the cylinder pot will cause a change of liquid levels in the side tube. When there is air both inside and outside the pot, the liquid levels are the same.

Explain why the levels of liquid change when hydrogen is placed *outside* the porous pot cylinder (Figure C1.19).

KEY WORDS

porous pot: an unglazed pot that has channels (pores) through which gases can pass.

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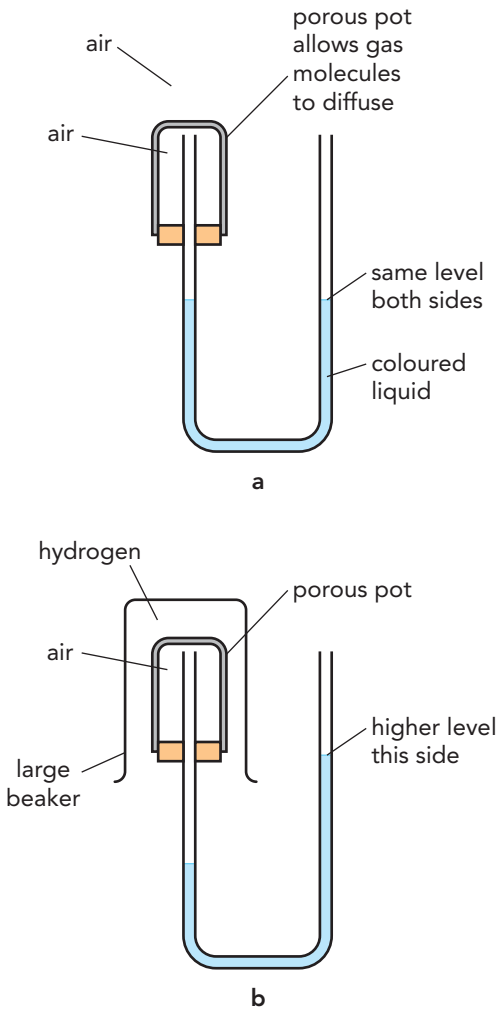

Figure C1.19: Gas diffusion through a porous pot, **a:** with air inside and outside the pot, **b:** with hydrogen outside the pot and air inside the pot.

ACTIVITY C1.01

The kinetic model of matter

Modelling the arrangement of the particles in a solid, liquid or gas is one way to help understand the properties of the different states of matter.

Working in a small group, create a model or visual representation that explains the movement of the particles in the different states. Think about:

- What could you use to represent the particles? (Balls or marbles in a tray or dish, circular pieces of card on a plate, groups of people, symbols perhaps?)
- How will you arrange the particles to demonstrate solids, liquids and gases?
- How could you represent the movement of the particles?

Your model, diagram or display should answer *three* of the following questions:

- Why can three states of matter exist?
- Why does it take time for a solid to melt?
- Why do solids not diffuse over a normal time period?
- What is different about substances that means that they each have different melting points?
- Different substances also have different boiling points. Is the reason for this similar to why they have different melting points?
- Why is it that you can feel a liquid cool when it evaporates in your hand?

After you have taken time to answer the questions, each group should choose one of the questions to demonstrate how your model works to the rest of the class.

REFLECTION

To understand some of the ideas introduced in this chapter, you need to be able to think about the behaviour of particles smaller than you can see.

- What strategies could you use to help you to visualise particles such as atoms and molecules?
- Are there any experiments which give you clues to the existence of these sub-microscopic particles?
- How useful do you find the different approaches?

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PROJECT C1.01 THE 'GOLDILOCKS PRINCIPLE'

How we experience the world around us depends upon the physical conditions and states in which substances exist. This is particularly true in the case of water. The Earth is the only body in our solar system where water exists in all three states of matter.

Work in a group of three or four. Use the internet to search for some information on the topics listed here. Then select one to research in detail.

The presence of water: What is distinctive about the physical conditions on Earth that mean that life could begin, and continue to exist, here? Why is water so important when thinking about how life began? Is Earth the only planet to have water and therefore life? Have other planets had water in their past? Recent space probes have been sent to try to find water on Mars and the moons of Jupiter and Saturn (Figure C1.20). Research the various missions to find out whether there are other planets in our solar system where life may have existed.

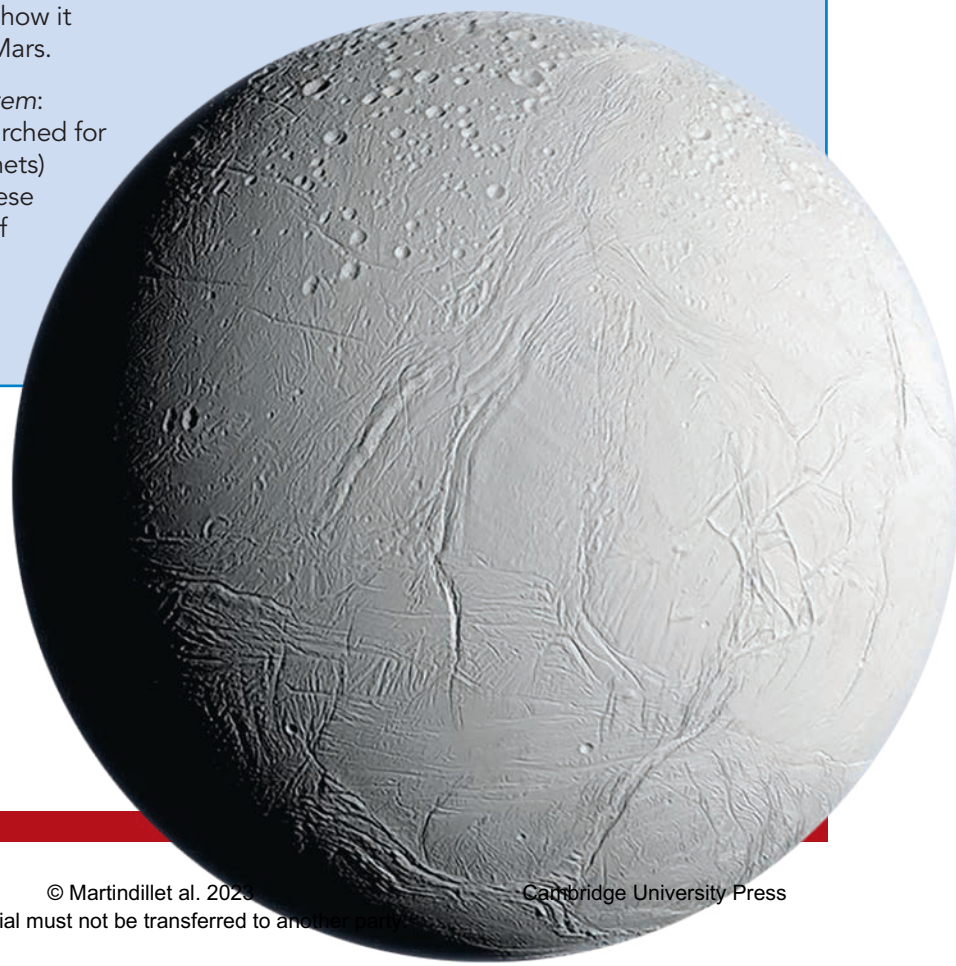
The 'Goldilocks Zone': Earth orbits the Sun at just the right distance for liquid water to exist on its surface. It is neither too hot nor too cold for this. Research this situation, which is known as the 'Goldilocks Zone', and its meaning. Then think about how it applies to the orbits of Venus, Earth and Mars.

Exo-planets and life beyond our solar system: The *Kepler* and *CHEOPS* probes have searched for planets outside our solar system (exo-planets) where life may have evolved. Research these missions and find out the characteristics of the other solar systems and planets they were hoping to find.

Decide how you will share out the tasks between the members of your group. Then bring your research together as an illustrated talk delivered to the whole class. A good illustrated talk should include the following:

- a clear structure
- a strong introduction that includes details of the question(s) you have investigated
- a short summary of the different areas you researched: make sure your points are in a sensible order
- a list of the key conclusions at the end
- the key information presented in a graphic format (e.g. as a table, chart, pie chart) instead of just text: illustrations will make your presentation much easier for your audience to understand and help them to remember your key points.

Figure C1.20: Saturn's moon Enceladus has a global ocean of liquid salty water beneath its crust.



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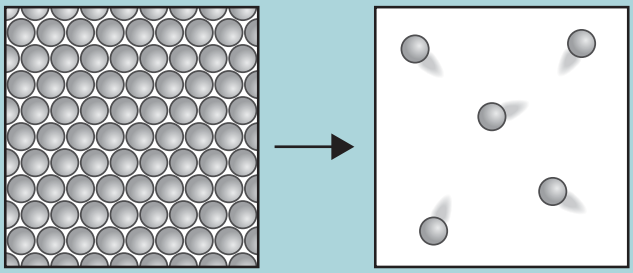
SUMMARY

There are three different physical states in which a substance can exist: solid, liquid or gas.
The structures of solids, liquids and gases can be described in terms of particle separation, arrangement and motion.
Different changes in state can take place, including melting and freezing, evaporation and condensation, and boiling.
Changes of state can be produced by changing conditions of temperature and/or pressure.
The kinetic particle model describes the idea that the particles of a substance are in constant motion and that the nature and amount of motion of these particles differs in a solid, liquid or gas.
Changing physical state involves energy being absorbed or given out. The temperature of the substance stays constant while the change takes place (as illustrated by the experimental construction of cooling curves).
Changes in temperature or the external pressure produce changes in the volumes of gases which can be explained in terms of the kinetic particle theory.
Diffusion in liquids and gases is the spreading of particles to fill all of the space available.
The rate of diffusion of a gas is dependent on molecular size. Molecules of lower mass diffuse more quickly than those of higher mass.

PRACTICE QUESTIONS

1 The figure shows one of the changes of physical state.



Identify which change of state is shown.

A boiling
B condensation
C melting
D evaporation **[1]**

COMMAND WORD

identify: name/select/recognise.

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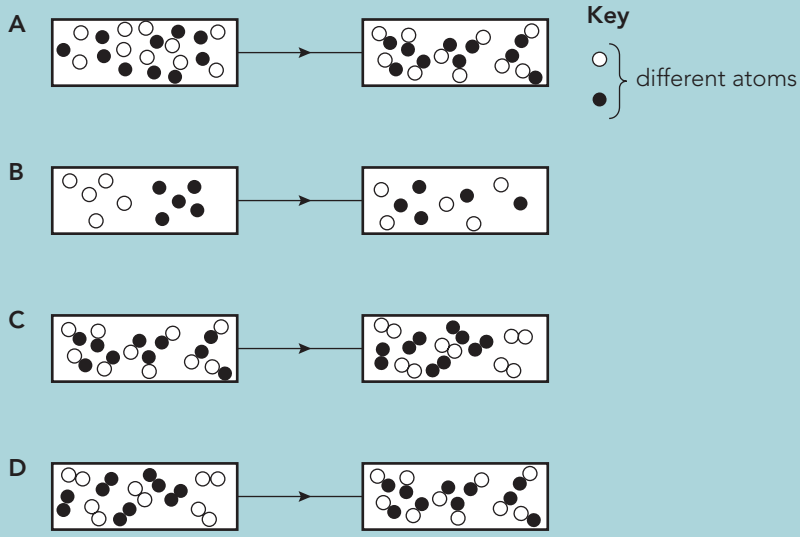
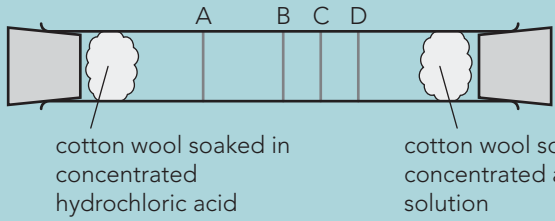
CONTINUED

2 Identify which of A–D in the figure shows the process of diffusion.



[1]

3 An experiment on the diffusion of ammonia and hydrogen chloride gases is carried out in a glass tube. The gases are given off by solutions held at each end of the tube.



When the two gases meet, they react to produce a white solid, ammonium chloride.

State which line (A–D) shows where the white solid is formed. [1]

COMMAND WORD

state: express in clear terms.

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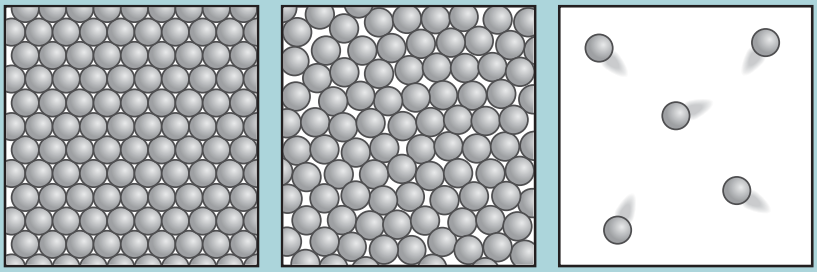
4 The figure shows the arrangement of particles in each state of matter.



solid liquid gas

a In a gas, the particles are moving rapidly and randomly. **Describe** the movement of the particles in a liquid. **[2]**

b State how the movement of the particles in a solid changes when it is heated. **[1]**

c **Give** the name of the process which happens when liquid water changes to water vapour at room temperature. **[1]**

d State what is meant by the term *freezing*. **[1]**

[Total: 5]

5 A teacher opens a bottle of perfume at the front of her laboratory. She notices a smell of flowers. A few minutes later, students at the front of the lab notice the smell too. Those students at the back do not notice it until later.

a Give the two processes that must take place for the smell from the perfume to reach the back of the laboratory. **[2]**

Later in the day, when the room had cooled, the teacher tries the same experiment with a different class. The smell is the same but it takes longer to reach the back of the lab.

b **Explain** this observation by reference to the particles of perfume. **[2]**

[Total: 4]

COMMAND WORDS

describe: state the points of a topic/give characteristics and main features.

give: produce an answer from a given source or recall/memory.

COMMAND WORD

explain: set out purposes or reasons/make the relationships between things clear/say why and/or how and support with relevant evidence.

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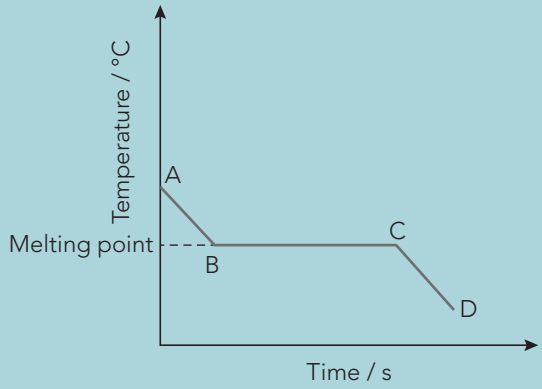
CONTINUED

6 The figure shows the change in temperature as a substance cools down.



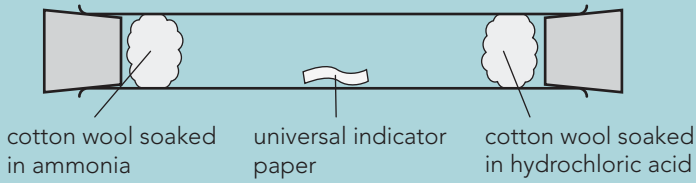
a Describe what is happening to the substance between C and D. **[2]**

b Describe what is happening to the particles of the substance between A and B. **[2]**

c State why the temperature does not change between B and C. **[1]**

[Total: 5]

7 Ammonia gas (M_r = 17) is a base that changes universal indicator to purple. Hydrogen chloride gas (M_r = 36.5) is an acid that changes universal indicator to red.



The figure shows an experiment done with these two gases. After two minutes, the universal indicator paper changed to purple.

a Explain why the universal indicator changed to purple and not red. **[3]**

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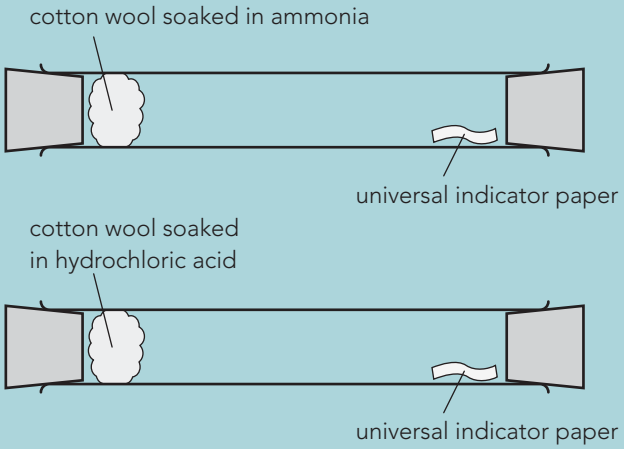
CONTINUED

b A further experiment is shown in the figure, measuring the rates of diffusion of ammonia and hydrogen chloride.



In the ammonia tube, the colour changed in 34 s. Give an estimate for how long it took for the indicator paper in the HCl tube to change colour, and justify your answer. **[2]**

[Total: 5]

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SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
state the major differences between the three states of matter	C1.01			
describe the changes of state observed with increasing or decreasing temperature	C1.01			
describe the effect of changes in temperature on the motion of particles in the different states of matter	C1.01			
interpret the shape of a cooling curve for a substance in terms of the kinetic particle theory	C1.01			
state the effects of changing temperature and pressure on the volume of a gas	C1.01			
explain, in terms of the kinetic particle theory, changes of state	C1.01			
explain, in terms of the kinetic particle theory, the effect of pressure and temperature on the volume of a gas	C1.01			
describe diffusion in gases and liquids	C1.02			
describe the effect of relative molecular mass on the rate of diffusion of a gas.	C1.02			

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C2

Atoms, elements and compounds

All learners study some content in this chapter

IN THIS CHAPTER YOU WILL:

- describe the difference between elements, compounds and mixtures
- describe the difference between metals and non-metals
- learn how atoms are the particles that make up the different elements
- study the structure of the atom
- learn about the relative charge and mass of the subatomic particles: the proton, neutron and electron
- learn how the electrons in an atom are organised in shells around the nucleus and determine the electronic configuration for an atom
- discover how the structure of any atom is defined by its proton number and mass number

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CONTINUED

- learn how the position in the Periodic Table relates to electronic configuration
- define isotopes as atoms of an element which have the same proton number but different numbers of neutrons
- use symbols to represent atoms and ions
- know that the chemical properties of isotopes of an element are the same, because their electronic configurations are the same
- understand that a covalent bond is formed by sharing a pair of outer electrons between two atoms, and describe bonding in simple molecules
- consider the properties of covalent species
- link the properties of covalent species to their structure and bonding
- understand the formation of ions
- understand that an ionic bond is the strong electrostatic force of attraction between oppositely charged ions, and represent the formation of ionic bonds using dot-and-cross diagrams
- consider the properties of ionic species
- link the properties of ionic species to their structure and bonding
- describe the structure of ionic compounds
- describe bonding in more complex molecules
- outline the giant covalent structures of diamond and graphite
- relate the uses of diamond and graphite to their structures
- describe metallic bonding
- relate the structure and bonding of metals to their properties.

BEFORE YOU START

Your earlier science courses will have introduced you to the world of the very small. In biology, you may have used a microscope to look at some slides to see the detail of leaves and small flies. In chemistry, we have seen that matter is made up of very small particles such as atoms or molecules.

We have also seen that the chemical formula for water is H_2O. From your previous studies, discuss the following questions to begin your study of the sub-microscopic world:

1 What do you understand that the formula of water means? What do the letters 'H' and 'O' mean in the formula? What is the difference between an atom and a molecule?

2 Are you aware of there being any particles that are smaller than an atom?

Extension

Can you use a molecular model-building kit or simple construction materials such as plasticine and drinking straws to build models of two or three simple molecules that you have encountered in your earlier science courses. It would be useful to build models of compounds such as:

- water
- ammonia
- methane.

Use the models to discuss what you remember of the type of bonding in the molecules and how the bonds are made.

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SCIENCE IN CONTEXT C2.01

Seeing is believing

Scientists have used new imaging techniques to 'see' atoms. Over the past few decades, the use of scanning tunnelling microscopes (STM) – a form of 'atomic microscopy' – has opened up the manipulation of the atomic world. In 1990, scientists at the Zurich laboratories of the multinational technology company IBM were able to create an 'atomic logo' using individual xenon atoms. The ability to move and position individual atoms has led to other images of interactions between atoms. One such image is the atomic 'corral' of 48 iron atoms arranged in a ring, which appeared in the international press (Figure C2.01).

New forms of atomic microscope have been developed, including the atomic force microscope and the quantum microscope. More recent advances using both scanning tunnelling and atomic force microscopes have led to the building of specific individual molecules. One such molecule was built to celebrate the 2012 Olympic Games in London. The single molecule was created using a combination of clever synthetic chemistry and state-of-the-art imaging techniques. As you would expect, this molecule, called olympicene, was made up of five rings and was about 100 000 times thinner than a human hair. Further advances in microscopy and image processing are anticipated that will allow us to observe digitally and 'see' the reactions between individual atoms.

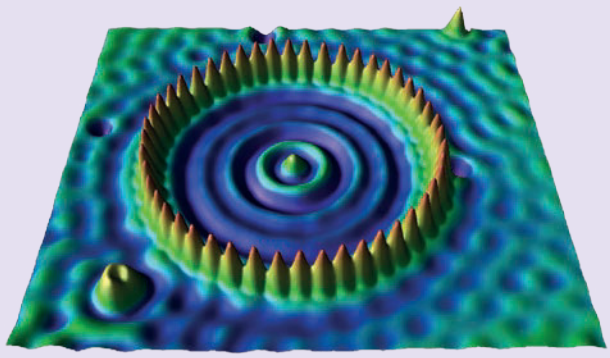

Figure C2.01: An atomic 'corral' of 48 iron atoms in a ring on a copper surface, and are viewed using a scanning tunnelling microscope (*Source*: IBM, published 1993).

Discussion questions

1 Which atoms do you think form the basic structure of olympicene? Think of the element that forms the basis of life.

2 Olympicene was made up of five hexagons arranged with shared sides as in a honeycomb. Predict the structure of the molecule. How many atoms do you think make up the skeleton structure of the five rings of olympicene?

C2.01 Elements, compounds and mixtures

Every substance around us is made up of atoms. These are the incredibly small particles from which all the material world is built (Figure C2.02). A substance made up of just one type of atom is called an **element**. Elements cannot be broken down into anything simpler by chemical reactions. There are now 118 known elements, but most of the known mass of the universe consists of just two elements, hydrogen (92%) and helium (7%). All the other elements contribute only 1% to the total. How a certain number of these elements concentrated together to form the Earth is of great interest and significance. There are 94 elements found naturally on Earth but just eight account for more than 98% of the mass of the Earth's crust. Two elements, silicon and oxygen, which are bound together in silicate rocks, make up almost three-quarters of the crust. Elements can combine to form **compounds** where the different types of atoms are chemically bonded together and the ratio of the types of atoms is a constant. As well as forming compounds, elements and molecules can mix together without chemically bonding to form **mixtures**.

KEY WORDS

element: a substance that cannot be further divided into simpler substances by chemical methods; all the atoms of an element contain the same number of protons.

compound: a substance formed by the chemical combination of two or more elements in fixed proportions.

mixture: two or more elements or molecules mixed together without being chemically bonded.

A mixture of iron and sulfur powders can contain various amounts of the two elements. The elements still keep their characteristic properties and can be separated using a magnet (Figure C2.03a). However, when a mixture of iron and sulfur is heated, a black compound called iron sulfide is formed, which is not attracted to a magnet (Figure C2.03b).

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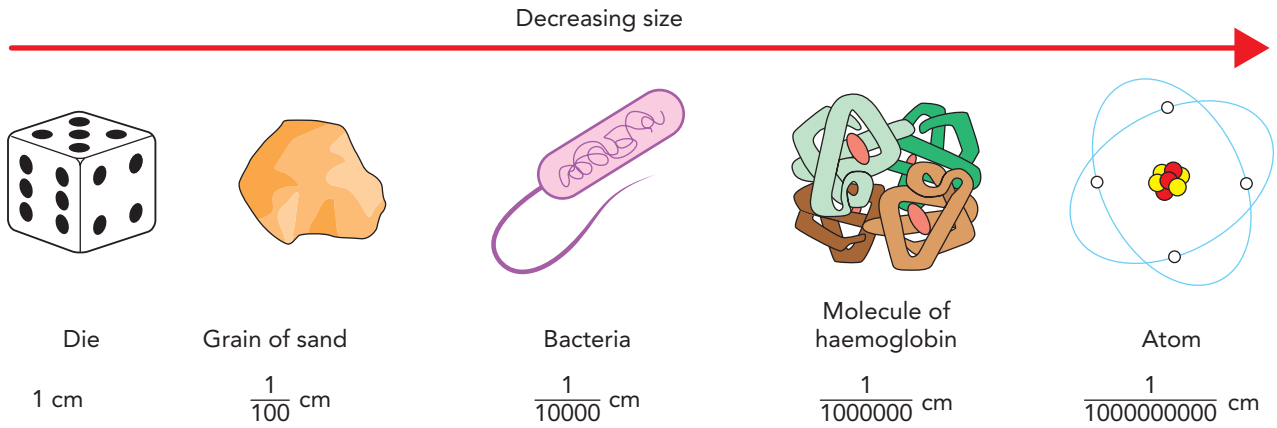

Figure C2.02: A sense of perspective of the size of the atom.

Figure C2.03 a: A mixture of iron and sulfur can be separated with a magnet. **b:** Iron powder and sulfur react together to form the black compound, iron sulfide, which is not magnetic.

Table C2.01 summarises how compounds and mixtures compare.

Compounds	Mixtures
a compound is a single substance	a mixture contains two or more substances
the composition is always the same	the composition can be varied
the formation involves a chemical reaction	no chemical change takes place when made
the properties are very different from the elements present in the compound	the properties of the substances making the mixture are still present
can only be broken down by chemical reactions	the substances present can be separated by physical methods

Table C2.01: A comparison of the nature of chemical compounds and mixtures of substances.

C2.02 Atomic structure and the Periodic Table

The structure of the atom

Our modern understanding of the structure of the atom (the atomic model) is based on the atomic theory put forward by the English chemist John Dalton in 1807. Dalton's idea was that atoms were the basic building blocks of the elements. He thought of them as indivisible particles that could join together to make molecules.

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Although certain parts of the theory have had to change as a result of what we have discovered since Dalton's time, his theory was one of the great leaps of understanding in chemistry.

Research since Dalton's time has shown that atoms are made up of several subatomic particles. The **electron** was discovered in 1897, followed soon after by the **proton**. Experiments then showed that an atom is mostly space occupied by the negatively charged electrons. The electrons are located in shells, surrounding a very small, positively charged **nucleus**. The nucleus is at the centre of the atom and contains almost all the mass of the atom. By 1932, when the **neutron** was discovered, it was clear that atoms consisted of three **subatomic particles**: protons, neutrons and electrons. These particles are universal – all atoms are made from them. The atom remains the smallest particle that shows the chemical characteristics of a particular element. Note that the term subatomic particles, while a useful description, is not an essential term to learn.

KEY WORDS

electron: a subatomic particle with negligible mass and a relative charge of −1; electrons are present in all atoms, located in the shells (energy levels) outside the nucleus.

proton: a subatomic particle with a relative atomic mass of 1 and a charge of +1 found in the nucleus of all atoms.

nucleus: (of an atom) the central region of an atom that is made up of the protons and neutrons of the atom; the electrons orbit around the nucleus in different 'shells' or 'energy levels'.

neutron: an uncharged subatomic particle present in the nucleus of atoms; a neutron has a mass of 1 relative to a proton.

subatomic particles: very small particles – protons, neutrons and electrons – from which all atoms are made.

ACTIVITY C2.01

Understanding atomic structure: a timeline of discovery

The discovery of the nature of the subatomic particles that make up all atoms took place in a relatively short space of time around the beginning of the 20th century. Working in a group, investigate this key period in the history of science and produce a timeline showing how our understanding of the model of the atom developed. You should include words and phrases such as:

indivisible, *subatomic particles*, *protons*, *neutrons*, *electrons*, *'plum pudding' model*, *nuclear model*, *nucleus*, *orbiting electrons*.

Key scientists to research include J. J. Thompson, Hantaro Nagaoka, Ernest Rutherford, James Chadwick and Niels Bohr.

On your timeline, try to answer the following questions:

1 What was remarkable about the structure of the atom suggested by the Geiger and Marsden gold foil experiments carried out in Rutherford's laboratory?

2 What is it about the nature of the neutron that made it the last of the particles to be discovered?

Once your timeline is complete, work individually to answer this question:

3 What do you think was the most important discovery? Justify your answer.

Peer assessment

Once your group has completed a timeline and you have all answered the questions as a group and individually (Question 3), exchange your group's timeline and answers with another group. Now review the timeline and the answers prepared by the other group. When you have finished your group review, share your feedback and comments with each other.

Points to consider when preparing your own timeline and in your review of the other group's work include:

- Are all the major discoveries and experiments included?
- Has the work and discoveries of any scientists other than those listed in the introduction been included?
- Are the events in the correct time sequence?
- Is the timeline presented in a clear way and can the information be quickly and easily understood?

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Protons, neutrons and electrons

The three subatomic particles are found in distinct regions of the atom. The protons and neutrons are located in the small nucleus at the centre of the atom. The electrons are present in the space surrounding the nucleus. The electrons are held within the atom by an electrostatic force of attraction between them and the positive protons in the nucleus.

The key characteristics of these three subatomic particles are listed in Table C2.02. You will note that protons and neutrons have almost the same mass. Both are given a relative mass of 1. Electrons have virtually no mass (1/1840 or 0.00054 of the mass of a proton). Protons and electrons have equal and opposite charges (+1 and −1, respectively). Neutrons are electrically neutral (have no charge).

Subatomic particle	Relative mass	Relative charge	Location in atom
proton	1	+1	in nucleus
neutron	1	0	in nucleus
electron	$\frac{1}{1840}$ (negligible)	−1	outside nucleus

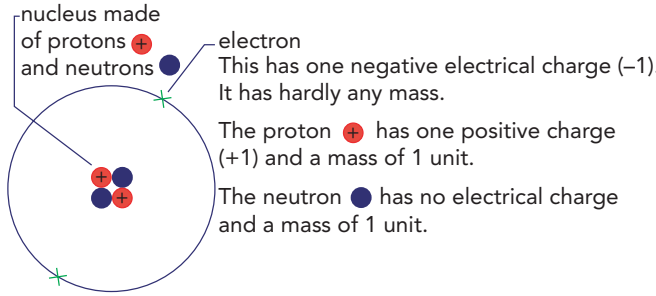
Table C2.02: Properties of the subatomic particles.

Although atoms contain electrically charged particles, the atoms themselves are electrically neutral (they have no overall charge). This must mean that in any atom there is an equal number of protons and electrons; the total positive charge on the nucleus (due to the protons) is balanced by the total negative charge of the electrons surrounding it.

The simplest atom is the hydrogen atom, which has one proton in its nucleus. It is the only atom that has no neutrons; it consists of one proton and one electron.

The next simplest atom is that of helium. This has two protons and two neutrons in the nucleus, and two orbiting electrons (Figure C2.04).

Lithium is the next simplest atom after helium. A lithium atom has three protons, four neutrons and three electrons. The subatomic arrangement of larger atoms gets more complicated with the addition of more protons and electrons. The number of neutrons required to hold the nucleus together increases as the atomic size increases. An atom of gold consists of 79 protons, 118 neutrons and 79 electrons.



A helium atom has these charged particles in it:

2 protons charge +2
2 electrons charge –2
these charges cancel out

We say the charges balance.
The atom has no overall electrical charge.

A helium atom has:

2 protons mass 2 units
2 neutrons mass 2 units
2 electrons with hardly any mass

So a helium atom has a total mass of:
2 + 2 = 4 units

Figure C2.04: Structure of a helium atom.

Proton number and nucleon number

Only hydrogen atoms have one proton in their nuclei. Only helium atoms have two protons. Indeed, only gold atoms have 79 protons. The number of protons in the nucleus of an atom determines which element it is. This important number is known as the **proton number** or **atomic number** of an atom. The proton number is given the symbol Z.

We have seen that protons alone do not make up all the mass of an atom. The neutrons in the nucleus also contribute to the total mass of the atom. Because protons and neutrons have the same relative mass, the mass of a particular atom depends on the total number of protons and neutrons present. Protons and neutrons are known as nucleons and the total number of protons and neutrons present is called the **mass number (or nucleon number)** of an atom. The mass number is given the symbol *A*.

KEY WORDS

proton number (or atomic number) (*Z*): the number of protons in the nucleus of an atom.

mass number (or nucleon number) (*A*): the total number of protons and neutrons in the nucleus of an atom.

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An important way of representing a particular atom of an element is to combine the chemical symbol of the element with the proton and mass numbers of the atom. The symbol Z, representing the proton number, and symbol A, representing the mass number, can be written alongside the symbol, in the general format ${}^{A}_{Z}\mathrm{X}$. Figure C2.05 shows how the structure of a helium atom is written in this way.

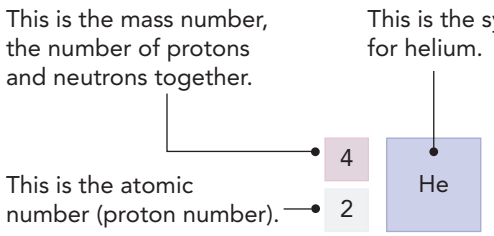

Figure C2.05: Representing the structure of a helium atom using the format ${}^{A}_{Z}\mathrm{X}$.

Using this format, an atom of lithium is represented as ${}^{7}_{3}\mathrm{Li}$. The atoms of carbon, oxygen and uranium are represented as ${}^{12}_{6}\mathrm{C}$, ${}^{16}_{8}\mathrm{O}$ and ${}^{238}_{92}\mathrm{U}$.

When the proton and mass numbers are known for the atoms of an element, we can work out the following:

- proton number (Z) = number of protons in the nucleus
- mass number (A) = number of protons + number of neutrons

It is also possible to establish two other important relationships:

- number of electrons = number of protons = atomic number
- number of neutrons = mass number – atomic number = $A - Z$

Table C2.03 shows the numbers of protons, neutrons and electrons in various elements. Note that the same rules apply even to the smallest or largest atoms.

Questions

C2.01 What are the relative masses of a neutron and electron, given that a proton has a mass of 1?

C2.02 How many protons, neutrons and electrons are there in an atom of phosphorus, which has a proton number of 15 and a mass number of 31?

C2.03 Explain the terms *atom* and *element*, and include a clear description of the relationship between the two terms.

C2.04 Explain why neutrons are important in making the nucleus of an atom stable. You need to consider the charges on the different subatomic particles present.

Electronic configuration of elements

The aurora borealis is a spectacular display seen in the sky in the far north (a similar phenomenon – the aurora australis – occurs in the southern hemisphere). It is caused by radiation from the Sun moving the electrons in atoms of the gases of the atmosphere.

Similar colour effects can be created in a simpler way in the laboratory by heating the compounds of some metals in a flame (Figure C2.06; see also the flame tests in Chapter C12).

The colours produced are due to electrons in the atom moving between two different electron shells.

In 1913, Niels Bohr, working with Ernest Rutherford, developed a theory to explain how electrons were arranged in atoms. This theory helps to explain how the colours in the flame test are produced.

Atom	Symbol	Proton number (Z)	Mass number (A)	Inside the nucleus:		Outside the nucleus: electrons (Z)
				Protons (Z)	Neutrons ($A - Z$)	
hydrogen	H	1	1	1	0	1
helium	He	2	4	2	2	2
lithium	Li	3	7	3	4	3
carbon	C	6	12	6	6	6
oxygen	O	8	16	8	8	8
calcium	Ca	20	40	20	20	20
gold	Au	79	197	79	118	79
uranium	U	92	238	92	146	92

Table C2.03: Subatomic composition and structure of atoms of different elements.

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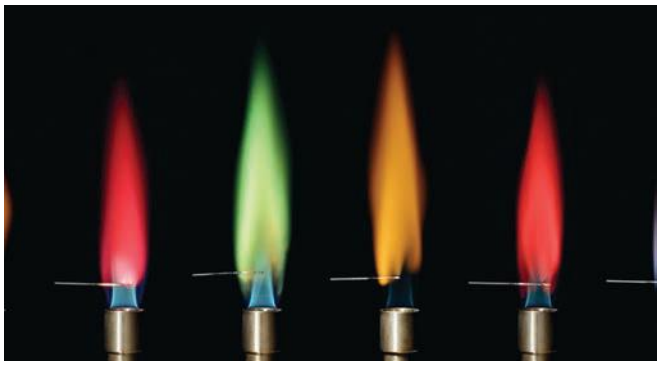

Figure C2.06: Some flame test colours for different elements.

A simplified version of Bohr's **atomic theory** of the arrangement of electrons in an atom can be summarised as follows (see Figures C2.07 and C2.08):

- Electrons are in orbit around the central nucleus of the atom.
- The electron orbits are called **electron shells (or energy levels)** and have different energies.
- The shells are filled starting with the one with lowest energy (closest to the nucleus).
- Shells that are further from the nucleus have higher energies.
- The first shell can hold only two electrons.
- The second and subsequent shells hold eight electrons (in atoms up to atomic number 20, it gets more complicated after this).
- Full shells are the most stable arrangement.

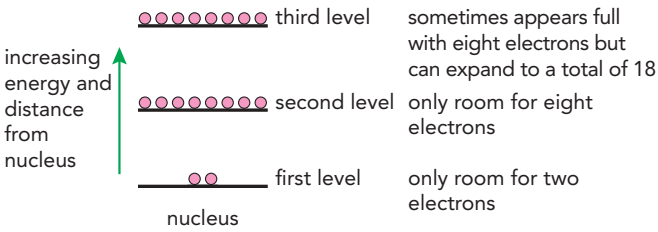

Figure C2.07: The different energy levels (shells) in an atom (not to scale). Electrons fill the shells starting from the one closest to the nucleus.

We represent the position of the electrons around the nucleus using the **electron configuration**. Here the number of electrons in each shell, from the innermost moving outwards, are given in order with a comma between them (Table C2.04, Figure C2.10).

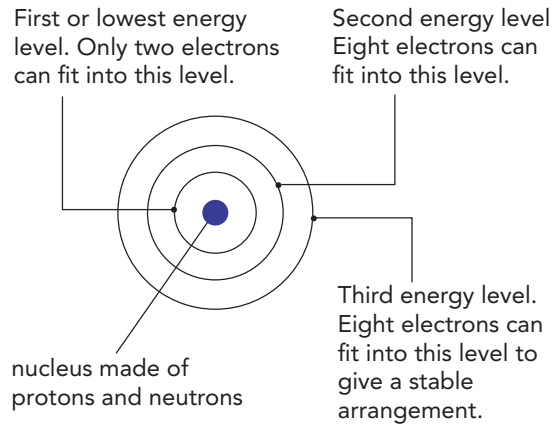

Figure C2.08: Bohr's atomic theory of the arrangement of electrons in an atom.

Further evidence was found that supported these ideas of how the electrons are arranged in atoms. The number and arrangement of the electrons in the atoms of the first 20 elements in the Periodic Table (see the example at the start of this book) are shown in Table C2.04.

For any atom, the combination of the arrangement of electrons in shells with the numbers of protons and neutrons makes it possible to draw a full subatomic representation. Figure C2.09 shows such a representation for an atom of carbon-12.

You can directly link the electronic configuration (Table C2.04) of an element to its position in the Periodic Table. The **group number** tells you the number of electrons in the outer shell (Figure C2.10) and the **period number** tells you the number of shells.

KEY WORDS

atomic theory: a model of the atom in which electrons can only occupy certain shells (or energy levels) moving outwards from the nucleus of an atom.

electron shells (energy levels): (of electrons) the allowed energies of electrons in atoms; electrons fill these shells (or levels) starting with the one closest to the nucleus.

electronic configuration: a shorthand method of describing the arrangement of electrons within the electron shells (or energy levels) of an atom; also referred to as electronic structure. This is given as number of electrons in the first shell, number of electrons in second shell, number of electrons in third shell, and so on.

group number: the number of the vertical column that an element is in on the Periodic Table.

period number: the horizontal row of the Periodic Table that an element is in.

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Element	Symbol	Atomic number (*Z*)	First shell	Second shell	Third shell	Fourth shell	Electronic configuration
hydrogen	H	1	•				1
helium	He	2	••				2
lithium	Li	3	••	•			2,1
beryllium	Be	4	••	••			2,2
boron	B	5	••	•••			2,3
carbon	C	6	••	••••			2,4
nitrogen	N	7	••	•••••			2,5
oxygen	O	8	••	••••••			2,6
fluorine	F	9	••	•••••••			2,7
neon	Ne	10	••	••••••••			2,8
sodium	Na	11	••	••••••••	•		2,8,1
magnesium	Mg	12	••	••••••••	••		2,8,2
aluminium	Al	13	••	••••••••	•••		2,8,3
silicon	Si	14	••	••••••••	••••		2,8,4
phosphorus	P	15	••	••••••••	•••••		2,8,5
sulfur	S	16	••	••••••••	••••••		2,8,6
chlorine	Cl	17	••	••••••••	•••••••		2,8,7
argon	Ar	18	••	••••••••	••••••••		2,8,8
potassium	K	19	••	••••••••	••••••••	•	2,8,8,1
calcium	Ca	20	••	••••••••	••••••••	••	2,8,8,2

Table C2.04: Electronic arrangements and configuration of the first 20 elements.

For example, silicon is in Group IV, period 3. Therefore, silicon has four electrons in its outer shell and three shells in total.

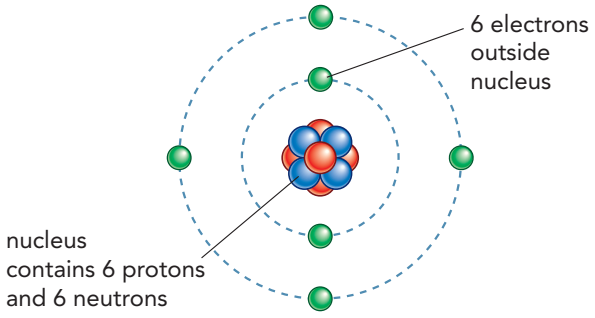

Figure C2.09: A visualisation of the subatomic structure of carbon-12.

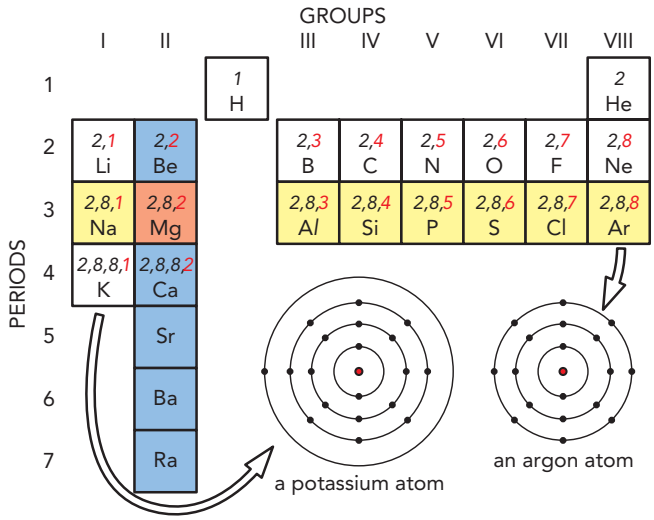

Figure C2.10: The relationship between an element's position in the Periodic Table and the electronic configuration of its atoms.

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The noble gas electronic configuration

Noble gases (Group VIII) are very unreactive gases. The atoms of the noble gas elements all have a very stable electron arrangement. They all have a 'full' outer shell of electrons. This means that they usually have eight electrons in their outer shell. Noble gas atoms do not make chemical bonds with the atoms of other elements by sharing or transferring their outer electrons.

KEY WORDS

noble gases: elements in Group VIII; a group of stable, very unreactive gases.

EXPERIMENTAL SKILLS C2.01

A chemical rainbow!

How are the spectacular colours of fireworks produced? The essential ingredients of fireworks are the explosive mixture and the metal compounds (also known as salts) that produce the distinctive colours. This experiment explores how different metal salts produce different colours as a result of different electron shifts within the atoms present.

You will need:

- a Bunsen burner
- a heat-resistant mat
- a nichrome wire loop
- dilute hydrochloric acid solution (0.1 mol/dm^3)
- a hand-held spectroscope (if available)
- several different solutions of metal salts (concentration 0.5 mol/dm^3): for example, NaCl(aq), KCl(aq), LiCl(aq), and $CuCl_2$(aq). A 0.5 mol/dm^3 $CaCl_2$(aq) solution and a 0.1 mol/dm^3 $BaCl_2$(aq) solution can also be used.

Safety

Wear eye protection throughout. Be careful with chemicals. Never ingest them and always wash your hands after handling them. All the salt solutions are low hazard at this concentration, except $CuCl_2$(aq), which is harmful and a skin/eye irritant.

Getting started

You will need a roaring flame on your Bunsen burner to carry out these tests. Practise getting this hottest flame using your burner by varying the air supply. If available, you should practise using a hand-held spectroscope before you take your practical observations.

Method

1 In a darkened room, place the Bunsen burner on a heat-resistant mat and light the Bunsen burner.

2 Heat a nichrome loop in a roaring Bunsen flame and then dip the loop into the dilute hydrochloric acid solution. Repeat this process several times to clean the loop and remove any contaminants.

3 Dip the loop into one of the salt solutions and then hold it in the hot part of the roaring Bunsen flame.

4 Observe the colour produced in the flame. Repeat using a hand-held spectroscope, noting the colour of the major lines produced. If a spectroscope is not available, note the colour you observe.

5 Rinse the loop with the dilute hydrochloric acid solution and flame it several times to clean away any remaining salt solution.

6 Continue to test the other salt solutions in the same way.

Questions

1 Is it the metal or non-metal present in the salts that is responsible for the colour emitted in the flame?

2 Table C2.05 shows the general relationship between the colour, frequency and energy of the light released. The bigger the change in energy level of the electrons, the greater the energy of the light released.

Which of the metal salt solutions produces light of the greatest energy? Put the salt solutions in order of the energy change involved, from the least to the greatest.

Colour	Frequency / THz
red	405–480
orange	480–510
yellow	510–530
green	530–600
cyan (blue-green)	600–620
blue	620–680
violet	680–790

energy increasing

Table C2.05: Frequency (in terahertz, THz) of the different colours of the visible spectrum.

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Questions

C2.05 **a** What are the maximum numbers of electrons that can fill the first and the second shells (energy levels) of an atom?

b What is the electron arrangement of a calcium atom, which has an atomic number of 20?

c How many electrons are there in the outer shells of the atoms of the noble gases argon and neon?

C2.06 By considering the subatomic particles present, explain why an atom of nitrogen is electrically neutral.

C2.07 The electronic diagrams of the atoms of four elements are shown in Figure C2.11.

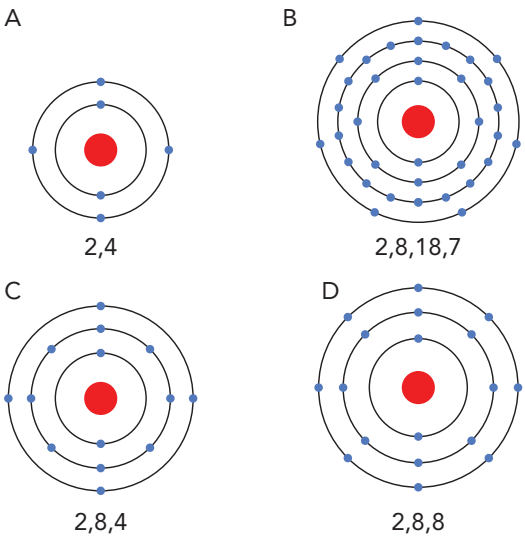

Figure C2.11: Electronic diagrams for four elements.

a Which *two* elements are in Group IV of the Periodic Table? Explain your answer.

b Which element is a noble gas? Explain your answer.

c Which of these elements is in Group VII of the Periodic Table? Explain your answer.

d Which *two* elements are in the third period (row) of the Periodic Table? Explain your answer.

e What is the proton number of element C? Explain your answer.

REFLECTION

Do you find diagrams help you to visualise the structure, movement and interaction of small objects such as atoms and molecules?

If diagrams do not help, can you think of other ways that could? Discuss your ideas with a partner.

C2.03 Isotopes

Pure samples of many elements (such as carbon, hydrogen and chlorine) contain atoms that have different masses. This is despite the fact that the atoms have the same numbers of protons and electrons. The different masses observed are the result of the presence of different numbers of neutrons in the nuclei of atoms of the same element. When this occurs, the atoms of the same element are called **isotopes**.

The isotopes of an element are defined by their difference in mass number. The isotopes are referred to using their mass number. For example, the isotopes of carbon are carbon-12, carbon-13 and carbon-14. Table C2.06 gives the details of the isotopes of several elements. Note that the symbol used to represent the isotope uses the mass and proton numbers as in Figure C2.05.

KEY WORD

isotopes: atoms of the same element that have the same proton number but a different nucleon number.

Characteristics of isotopes

Many elements have naturally occurring isotopes. Hydrogen, the simplest element, has two naturally occurring isotopes: hydrogen and deuterium (Figure C2.12). A third isotope, tritium, can be made artificially.

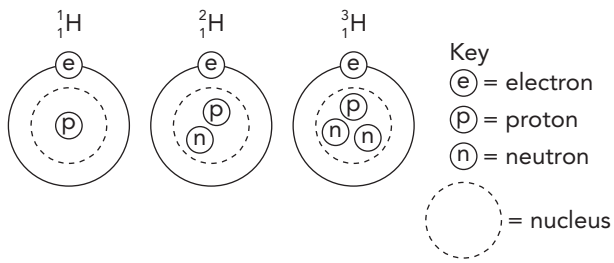

Figure C2.12: Isotopes of hydrogen: hydrogen ($^{1}_{1}H$), deuterium ($^{2}_{1}H$) and tritium ($^{3}_{1}H$).

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Element	Isotopes		
hydrogen	hydrogen (99.99%)	deuterium (0.01%)	tritium*
	$^{1}_{1}H$	$^{2}_{1}H$	$^{3}_{1}H$
	1 proton	1 proton	1 proton
	0 neutrons	1 neutron	2 neutrons
	1 electron	1 electron	1 electron
carbon	carbon-12 (98.9%)	carbon-13 (1.1%)	carbon-14(*) (trace)
	$^{12}_{6}C$	$^{13}_{6}C$	$^{14}_{6}C$
	6 protons	6 protons	6 protons
	6 neutrons	7 neutrons	8 neutrons
	6 electrons	6 electrons	6 electrons
neon	neon-20 (90.5%)	neon-21 (0.3%)	neon-22 (9.2%)
	$^{20}_{10}Ne$	$^{21}_{10}Ne$	$^{22}_{10}Ne$
	10 protons	10 protons	10 protons
	10 neutrons	11 neutrons	12 neutrons
	10 electrons	10 electrons	10 electrons
chlorine	chlorine-35 (75%)	chlorine-37 (25%)	
	$^{35}_{17}Cl$	$^{37}_{17}Cl$	
	17 protons	17 protons	
	18 neutrons	20 neutrons	
	17 electrons	17 electrons	
Tritium and carbon-14 atoms are radioactive isotopes because their nuclei are unstable.			

Table C2.06: Several elements that exist as mixtures of isotopes.

The isotopes of an element have the same chemical properties because they contain the same number of electrons. Therefore, they have the same electronic configuration. It is the number of electrons in an atom that determines the way in which it forms bonds and reacts with other atoms. However, some physical properties of the isotopes *are* different.

Questions

C2.08 Look at Figure C2.13. Which of the diagrams A, B or C represents the nucleus of an atom of the carbon-14 isotope?

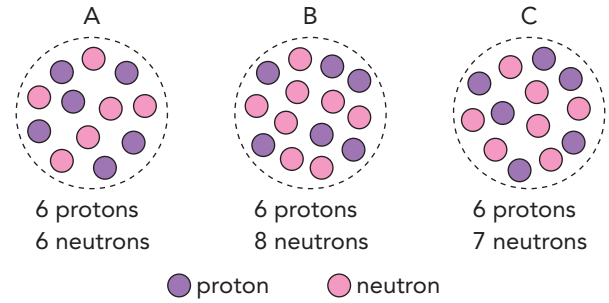

Figure C2.13: The nuclei of carbon isotopes.

C2.09 What is the difference in terms of subatomic particles between an atom of chlorine-35 and an atom of chlorine-37?

C2.10 Carbon-12 and carbon-14 are different isotopes of carbon. How many electrons are there in an atom of each isotope?

C2.04 Chemical bonding

Elements combine to make all the compounds around us. The simplest compounds that we are all familiar with, and the complex molecules that determine our biology, are all made from these elements. Each compound is made of particular elements, always combined in the same proportions. Simple compounds, such as water, ammonia and methane, begin to show the variety that can be achieved when the atoms of elements combine together. Water is formed from hydrogen and oxygen. Each water molecule contains two hydrogen atoms bonded to an oxygen atom (Figure C2.14).

Figure C2.14: A water molecule consists of two hydrogen atoms (white) bonded to an oxygen atom (red).

When different elements react together to form a compound, their characteristic properties are replaced by those of that compound. Importantly, the compound formed has properties that bear no direct relationship to those of the elements that make it up. A clear example of this is sodium chloride (common salt) (Figure C2.15). Sodium is a highly reactive metal. On contact with water, sodium fizzes violently and may even cause a flame as the reaction takes place. The toxic gas chlorine was once used as a chemical weapon, and is still used to kill harmful microbes in water treatment.

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Yet the compound of these two elements, sodium chloride, is a crystalline solid that is not only harmless enough to flavour food, but is in fact essential for life.

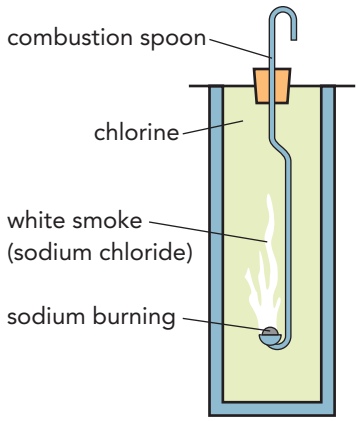

Figure C2.15: Burning sodium in chlorine gas produces sodium chloride (common or table salt).

The formulae of the compounds sodium chloride and water are NaCl and H_2O, respectively. Here you begin to see how formulae are constructed using the chemical symbol of each element. Both formulae indicate the ratio of the atoms involved in making the compound. We will look at **chemical formulae** in more detail in Chapter C3.

Chemical bonding involves the outer electrons of each atom. As we examine a range of substances, we shall see that, whatever type of bonding holds the structure together, it is the outer electrons that are used. The diversity of the material world is produced by the different ways in which atoms can join together. There are two types of compound we will consider:

- molecular compounds, where the atoms are bonded together by shared electrons: water, ammonia and methane are examples of simple molecular compounds
- ionic compounds, where many ions (charged atoms) are held together in a regular structure due to the charges on the ions: sodium chloride is an example of an ionic compound.

KEY WORDS

chemical formula: a shorthand method of representing chemical elements and compounds using the symbols of the elements.

chemical bonding: the strong forces that hold atoms (or ions) together in the various structures that chemical substances can form; this includes metallic bonding, covalent bonding and ionic bonding.

C2.05 Ions and ionic bonds

Two major types of bond hold compounds together. The first is covalent bonding, which involves the sharing of electrons, usually between atoms of non-metals. However, compounds combining metals and non-metals involve a second type of bonding known as **ionic bonding**. In ionic bonding, electrons are transferred from one atom to another, forming **ions**.

Ionic compounds are held together by **electrostatic forces** of attraction between the oppositely charged ions.

KEY WORDS

ionic bonding: a strong electrostatic force of attraction between oppositely charged ions.

ions: charged particles made from an atom, or groups of atoms (compound ions), by the loss or gain of electrons.

electrostatic forces: strong forces of attraction between particles with opposite charges; such forces are involved in ionic bonding.

Formation of ions

An ion is an electrically charged particle. Ions are formed when atoms lose or gain electrons. We saw earlier that atoms with a noble gas electronic configuration are particularly stable and unreactive. Noble gas atoms, apart from helium, have eight electrons in their outer shells. Most atoms do not have this arrangement of outer electrons and so are more reactive. One way of gaining this noble gas structure is to completely transfer electrons from one atom to another. This leads to the formation of positive ions, called cations, and negative ions, called anions.

Atoms of metals in Group I all have one electron in their outer energy level. Figure C2.16 shows the loss of an outer electron from a sodium atom. This results in the formation of a positive sodium cation (Na^+) which has a complete outer shell.

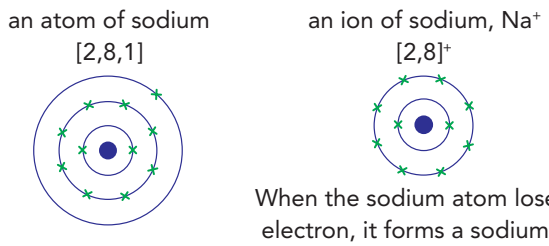

Figure C2.16: A sodium atom loses an electron to become a sodium ion.

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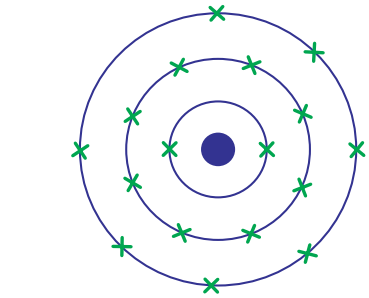
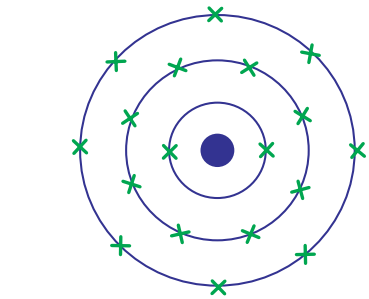
The sodium ion has a single positive charge because it now has just 10 electrons in total, but there are still 11 protons in the nucleus of the atom. It also now has a complete outer shell.

Halogen atoms in Group VII of the Periodic Table have seven outer electrons. They can achieve a stable noble gas configuration by gaining an electron (Figure C2.17), forming an anion. The chloride ion (Cl^-) formed has a negative charge because it has one more electron (18) than there are protons in the nucleus (17).



The chlorine atom [2,8,7] needs to gain an electron to make it more stable.

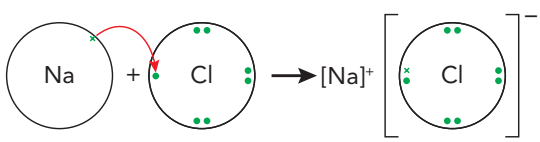


This is an ion of chlorine $[2,8,8]^-$.

Figure C2.17: A chlorine atom gains an electron to become a chloride ion.

Ionic compounds

Ionic compounds involve the transfer of electrons from one atom to another. This transfer results in the formation of positive and negative ions. In the case of sodium chloride, an electron is transferred from the sodium atom to the chlorine atom. This forms sodium (Na^+) and chloride (Cl^-) ions (Figure C2.18).



sodium chloride (NaCl)

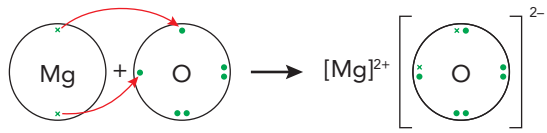
Figure C2.18: Transfer of electrons from a sodium atom to a chlorine atom to form ions.

The sodium ion then has the stable electron arrangement (2,8) of a neon atom. The chloride ion formed (electron arrangement 2,8,8) has the electron arrangement of an argon atom. The positive and negative ions in sodium chloride are held together by the electrostatic attraction between opposite charges. Similar diagrams can be drawn for the ionic bonding in other compounds between Group I metals and Group VII non-metals: the alkali metals and the halogens.

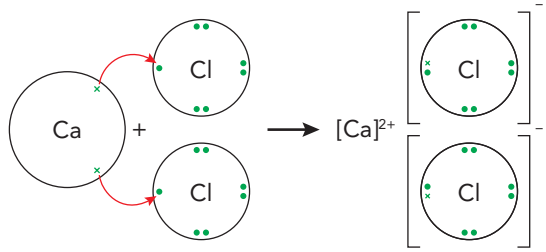
The important features of ionic bonding are:

- The electrons involved in the formation of ions are those in the outer shell of the atoms.
- Metal atoms lose their outer electrons to become positive ions. The charge is equal to the number of electrons lost.
- Generally, atoms of non-metals gain electrons to become negative ions. The charge is equal to the number of electrons gained.
- Ions formed achieve the stable electron arrangement of the nearest noble gas to them in the Periodic Table.

More complex ionic compounds than those formed between the alkali metals and the halogens involve the transfer of a greater number of electrons. Care is needed when you draw diagrams showing the bonding in such compounds. Figure C2.19 shows two examples of such compounds. In the first case, two electrons are being transferred from a magnesium atom to an oxygen atom to form magnesium oxide (MgO). A magnesium atom has two electrons in its outer shell. An oxygen atom has six outer electrons. By transferring two electrons from magnesium to oxygen to complete its outer shell, both the magnesium and oxide ions formed have the configuration of a neon atom.



magnesium oxide (MgO)



calcium chloride ($CaCl_2$)

Figure C2.19: Diagrams showing the formation of ionic bonds in magnesium oxide and calcium chloride. Only the outer electrons are shown.

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Physical properties of ionic compounds

Ionic compounds (such as sodium chloride) are solids at room temperature. The ions arrange themselves into a regular lattice structure (Figure C2.20). In this regular arrangement, each ion is surrounded by ions of the opposite charge. The whole structure is held together by the electrostatic forces of attraction that occur between particles of opposite charge.

Knowing how atoms combine to make different types of structure helps us begin to understand why substances have different physical properties. Table C2.07 shows the key properties of ionic compounds.

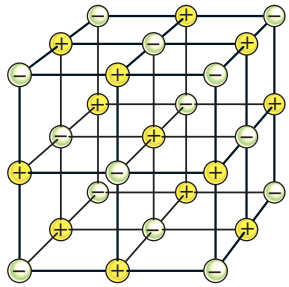

Figure C2.20: An ionic lattice where each ion is surrounded by ions of opposite charge.

Properties of typical ionic compounds	They are solids at room temperature.
	They have high melting and boiling points.
	They are often soluble in water (not usually soluble in organic solvents, e.g. ethanol, methylbenzene).
	They conduct electricity when molten or dissolved in water (not when solid).
Reason for these properties	There is a regular arrangement of the ions in a lattice. Ions with opposite charge are next to each other.
	Ions are attracted to each other by strong electrostatic forces. Large amounts of energy are needed to separate them.
	Water is attracted to charged ions and therefore many ionic solids dissolve in water.
	In the liquid or solution, the ions are free to move about. They can move towards the electrodes when a voltage is applied.

Table C2.07: The properties of ionic compounds.

C2.06 Simple molecules and covalent bonds

We have learnt that each element contains a defined type of atom (with a defined number of protons). However, most elements are not simply made up of separate atoms individually arranged. Elements such as oxygen (O_2) and hydrogen (H_2) consist of **diatomic molecules**. Indeed, the only elements that are made up of individual atoms moving almost independently of each other are the noble gases (Group VIII). Noble gas electron arrangements are very stable and so their atoms do not combine with each other.

For non-metallic elements, the type of bonding involved is **covalent bonding**. Covalent bonding is also the bonding used in compounds between one non-metal and another. Here, a pair (or multiple pairs) of electrons are shared between the atoms involved in the bond.

KEY WORDS

diatomic molecules: molecules containing two atoms, e.g. hydrogen, H_2.

covalent bonding: chemical bonding formed by the sharing of one or more pairs of electrons between atoms.

Simple molecular elements

Hydrogen normally exists in the form of diatomic molecules (H_2). Two atoms bond together by sharing their electrons. The electron shells overlap with each other, and a molecule is formed (Figure C2.21).

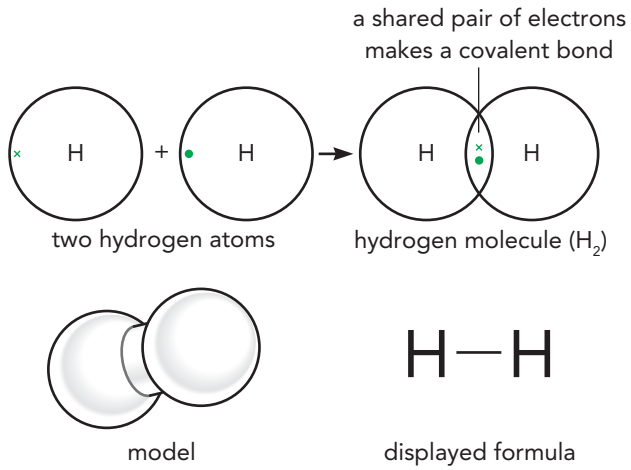

Figure C2.21: The hydrogen molecule is formed by sharing the electrons between the atoms.

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Through this sharing, each atom gains a share in two electrons. This is the number of electrons in the outer shell of helium, the nearest noble gas to hydrogen. (Remember that the electron arrangement of helium is very stable; helium atoms do not form He_2 molecules.) Sharing electrons like this is known as covalent bonding. Covalent bonds are held together by the forces of attraction between the shared negative electrons and the nuclei involved.

The main features of covalent bonding are:

- The bond is formed by the sharing of a pair of electrons between two atoms, leading to noble gas electronic configurations.
- Generally, each atom contributes an equal number of electrons to each bond (one electron each for single bonds).

Many non-metallic elements form diatomic molecules. However, elements other than hydrogen form bonds in order to gain a share of eight electrons in their outer shells. This is the number of electrons in the outer shell of all the noble gases apart from helium. Thus, the halogens (Group VII) form covalent molecules (Figure C2.22). In forming these molecules, each atom gains a share in eight electrons in its outer shell. A **dot-and-cross diagram** can be drawn showing the outer electrons only, because the inner electrons are not involved in the bonding.

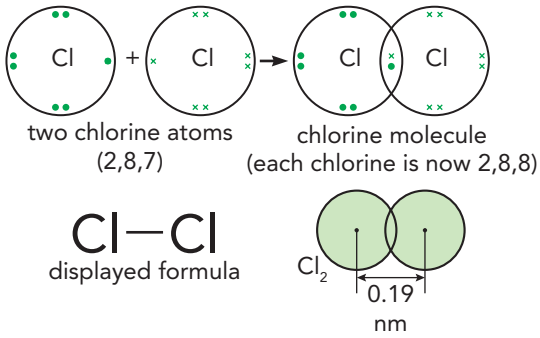

Figure C2.22: The formation of the covalent bond in chlorine molecules (Cl_2).

KEY WORDS

dot-and-cross diagram: a diagram drawn to represent the bonding in a molecule, or the electrons in an ion; usually, only the outer electrons are shown and they are represented by dots or crosses depending on which atom they are from.

Molecules of hydrogen and the halogens are each held together by a single covalent bond. Such a single bond uses two electrons, one from each atom. The bond can be drawn as a single line between the two atoms.

When molecules of oxygen (O_2) or nitrogen (N_2) are formed, more electrons have to be used in bonding if the atoms are to gain a share of eight electrons. These molecules are held together by a double bond (O_2) or a triple bond (N_2) (Figure C2.23).

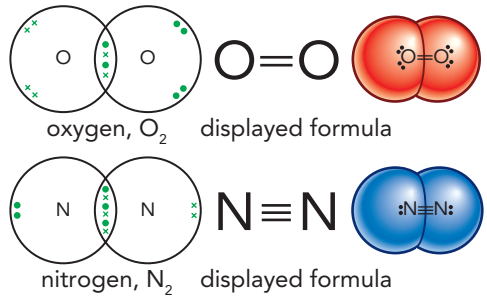

Figure C2.23: Structures of oxygen (O_2) and nitrogen (N_2) molecules involve multiple covalent bonding. An oxygen molecule contains a double bond; a nitrogen molecule contains a triple bond.

Simple covalent compounds

In simple covalent molecules, the atoms share electrons to achieve a more stable arrangement of electrons, most often that of a noble gas. The formation of hydrogen chloride (HCl) molecules involves the two atoms sharing a pair of electrons (Figure C2.24).

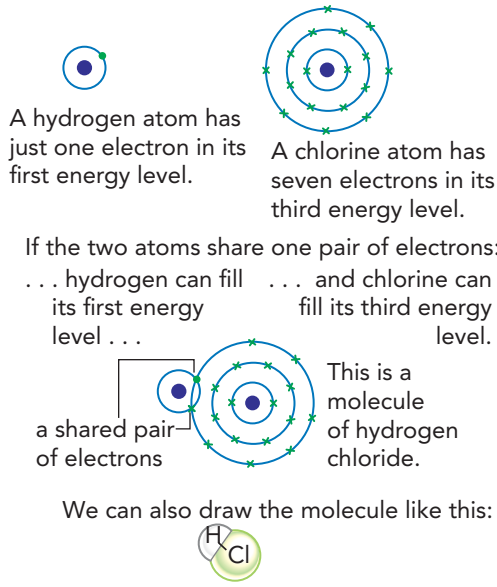

Figure C2.24: Hydrogen and chlorine atoms share a pair of electrons to form a molecule of hydrogen chloride.

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The examples shown in Figure C2.25 illustrate different ways of representing this sharing. They also show how the formula of the compound corresponds to the numbers of each atom in a molecule.

We can also use dot-and-cross diagrams to represent more complex molecules such as methanol, CH_3OH (Figure C2.26).

Earlier, we saw that multiple covalent bonds can exist in molecules of the elements oxygen and nitrogen. Multiple covalent bonds can also exist in compounds. Carbon dioxide molecules are held together by double bonds between the atoms (Figure C2.26) with the atoms donating two electrons to each bond they form. Ethene molecules contain a mixture of single and double bonds.

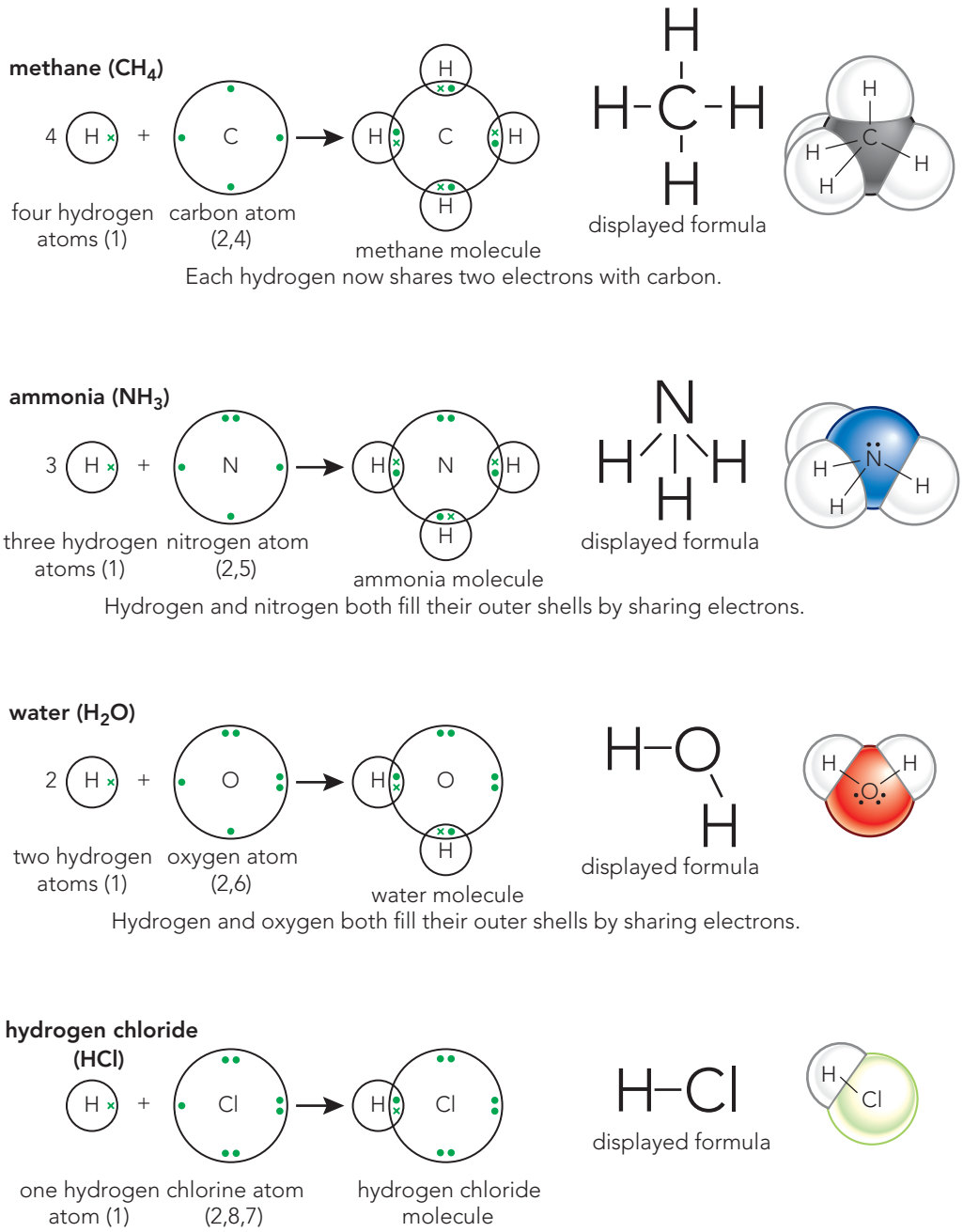

Figure C2.25: Examples of the formation of simple covalent molecules. Again, only the outer electrons of the atoms are shown.

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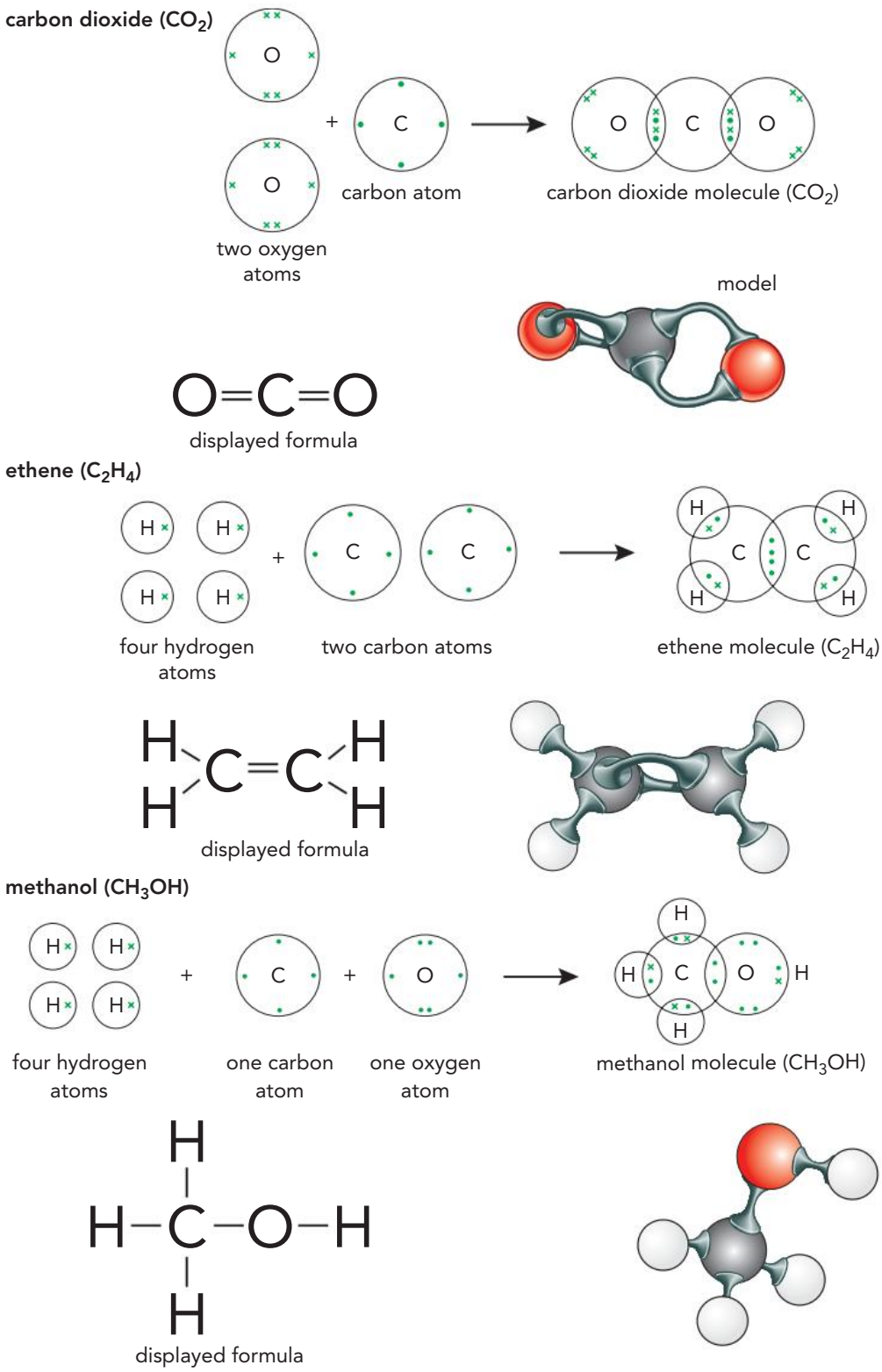

Figure C2.26: Formation of the carbon dioxide, ethene and methanol molecules, showing the outer electrons only. Ball-and-stick models can be used to show the structures.

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Questions

C2.11 In a pure sample of any element, what is the most important feature of all the atoms present?

C2.12 A gas is made up of simple molecules that have the formula NOCl. Which of the diagrams A–D in Figure C2.27 correctly represents the molecules of NOCl?

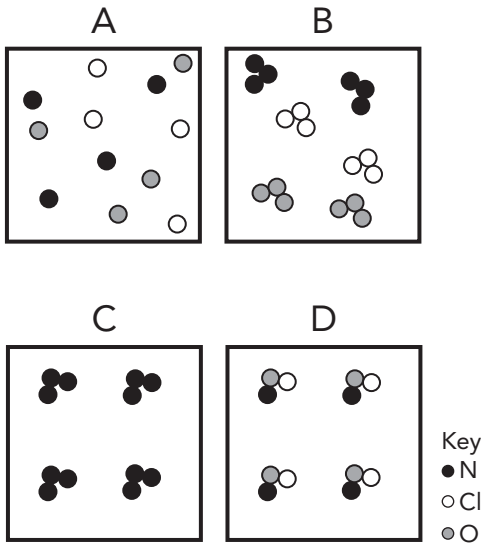

Figure C2.27: Representations of various gases.

C2.13 Methane is the simplest hydrocarbon (a compound of carbon and hydrogen *only*) and has the formula CH_4 (Figure C2.28).

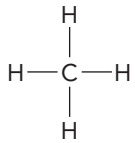

Figure C2.28: The structure of a methane molecule.

What is the total number of electrons involved in the bonding in methane?

A 10
B 2
C 8
D 4

C2.14 Covalent bonding involves electrons being shared between the atoms bonded together. Methane is made up of covalently bonded molecules. Which of the diagrams A–D in Figure C2.29 represents the bonding in methane?

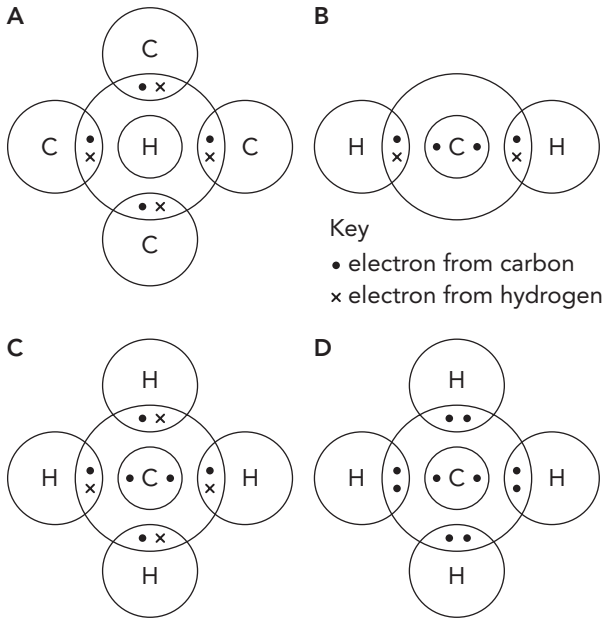

Figure C2.29: The possible bonding in methane.

Physical properties of simple covalent compounds

One property of simple molecular compounds is that they have low melting points and boiling points and are often liquids or gases at room temperature.

When considering this property of simple molecular compounds, it is important to be aware of the two levels of interactive force involved. The covalent bonds within the molecule are strong and difficult to break. However, the forces between the molecules, the intermolecular forces, are only weak and are relatively easily broken. If you think back to the discussion of changes of state in Chapter C1, you will understand that the presence of weak intermolecular forces gives rise to low melting and boiling points. Because the forces between the molecules are weak, only a small amount of energy is needed to enable the molecules to move away from each other. Other properties are given in Table C2.08.

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Properties of simple covalent compounds	They are often liquids or gases at room temperature.	They have low melting and boiling points.	They do not conduct electricity.
Reason for these properties	These substances are made of simple molecules. The atoms are joined together by covalent bonds.	The forces between the molecules (intermolecular forces) are only very weak. Not much energy is needed to move the molecules further apart.	There are no ions present to carry the current.

Table C2.08: Some properties of simple covalent compounds.

Questions

C2.15 The boiling point of a substance relates to the type of bonding present in the substance. Two elements, X and Y, combine to form a liquid with the relatively low boiling point of 120 °C. Which of the alternatives A–D in Table C2.09 correctly describes this substance?

	Type of element		Type of bonding
	X	Y	
A	metal	metal	covalent
B	non-metal	non-metal	ionic
C	non-metal	non-metal	covalent
D	metal	non-metal	ionic

Table C2.09: Possible descriptions of the make-up of a liquid.

C2.16 Draw dot-and-cross diagrams of the ionic bonding in the following compounds and give their formula:

a lithium fluoride

b sodium bromide

c potassium chloride

C2.17 Figure C2.30 shows the structure of a molecule of methanoic acid.

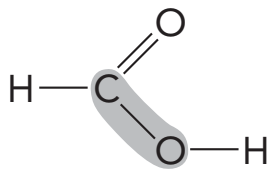

Figure C2.30: Methanoic acid.

Table C2.10 lists four descriptions of the bonds formed between the carbon and oxygen atoms in the shaded region of the structure. Which of the descriptions A–D is correct?

	Carbon	Oxygen
A	shares 1 electron with hydrogen and 3 electrons with oxygen	shares 1 electron with hydrogen and 1 electron with carbon
B	shares 2 electrons with hydrogen and 2 electrons with oxygen	shares 1 electron with hydrogen and 2 electrons with carbon
C	shares 1 electron with hydrogen and 3 electrons with oxygen	shares 1 electron with hydrogen and 2 electrons with carbon
D	shares 2 electrons with hydrogen and 2 electrons with oxygen	shares 1 electron with hydrogen and 1 electron with carbon

Table C2.10: Bonding in methanoic acid.

ACTIVITY C2.02

Mind-mapping chemical bonding

Mind-mapping is a technique that allows you to visually organise your thoughts and share information on a complex topic. Figure C2.31 shows part of a mind map on atoms, ions and molecules.

A section of the map has been drawn based on the ideas behind atomic theory.

1 Copy the current map and complete the 'atomic theory' group by filling in the missing words.

2 Draw new clouds on the unoccupied branches: the upper branch labelled 'ionic bonding' and the middle branch labelled 'covalent bonding'.

3 Add boxes around each new cloud giving the key details of that type of bonding. Include as many ideas as you can.

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CONTINUED

4 Using another coloured pen, can you make a new link between one of the lower boxes and the middle cloud?

You could also try to create your own mind map using online tools and resources available on the internet.

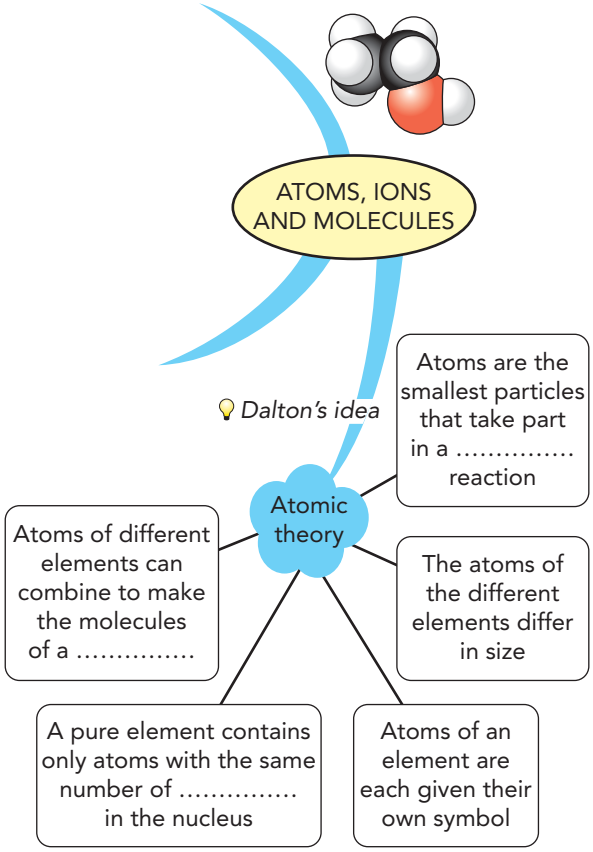


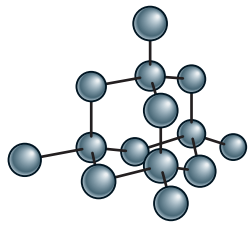
Figure C2.31: A mind map on atoms, ions and molecules.

C2.07 Giant covalent structures

Macromolecules, or giant molecular crystals, are held together by strong covalent bonds. This type of structure is shown by some elements (e.g. carbon, in the form of diamond and graphite) and also by some compounds (e.g. silica, SiO_2).

Structures of diamond and graphite

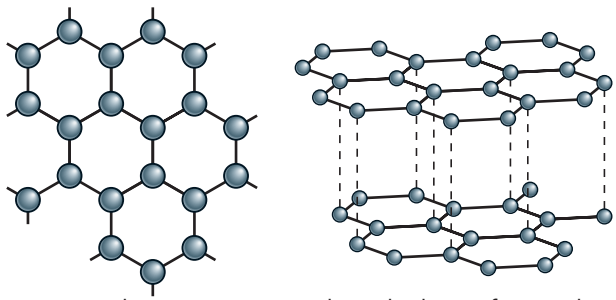
In diamond, each carbon atom is attached to four others. The atoms are arranged tetrahedrally (Figure C2.32) and all the atoms are bonded to each other via covalent bonds.



diamond

Figure C2.32: The tetrahedral structure of diamond.

Graphite is a different form of carbon that does conduct electricity (Table C2.11). The carbon atoms are arranged in a different way in the molecular structure of graphite. They are arranged in flat layers of linked hexagons (Figure C2.33).



one layer how the layers fit together

Figure C2.33: Layered structure of graphite.

Each graphite layer is a two-dimensional giant molecule. Within these layers, each carbon atom is bonded to three others by strong covalent bonds. Between the layers there are weaker forces of attraction. The layers are able to slide over each other easily.

Uses of diamond and graphite

The properties of diamond are due to the fact that the strong covalent bonds extend in all directions through the whole crystal. Diamond has a very high melting point. It is also very hard and is used in cutting tools. The bonds are rigid, however, and these structures are much more brittle than giant metallic lattices. All the outer electrons of the atoms in these structures are used to form covalent bonds. There are no electrons free to move. Diamond is therefore a typical non-metallic element. It does not conduct electricity (Table C2.11).

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	Diamond		Graphite	
	Properties	Uses	Properties	Uses
Appearance	colourless, transparent crystals that sparkle in light	in jewellery and ornamental objects	dark grey, shiny solid	
Hardness	the hardest natural substance	in drill bits, diamond saws and glasscutters	soft: the layers can slide over each other and the solid has a slippery feel	in pencils, and as a lubricant
Electrical conductivity	does not conduct electricity		conducts electricity	as electrodes and for the brushes in electric motors

Table C2.11: A comparison of the properties and uses of diamond and graphite.

Because graphite layers are able to slide over each other easily, graphite feels slippery and can be used as a lubricant. Graphite is used in pencils. When we write with a pencil, thin layers of graphite are left stuck to the paper. The most distinctive property, however, results from the fact that there are free electrons not used for covalent bonding by the atoms in the layers. These electrons can move between the layers, carrying charge, so that graphite can conduct electricity in a similar way to metals.

C2.08 Metallic bonding

Metal atoms have relatively few electrons in their outer shells. When they are packed together, each metal atom loses its outer electrons into a **'sea' of delocalised electrons**. Having lost electrons, the atoms present are no longer electrically neutral. They become positive ions because they have lost electrons but the number of protons in the nucleus has remained unchanged. Therefore, the structure of a metal is made up of positive ions packed together. These ions are surrounded by electrons, which can move freely between the ions. These free electrons are delocalised (not restricted to orbiting one positive ion) and form a kind of electrostatic 'glue' holding the structure together in what is called **metallic bonding** (Figure C2.34).

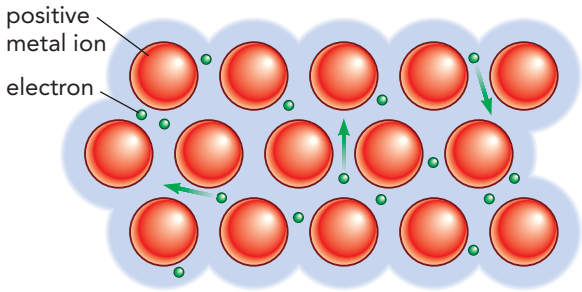

Figure C2.34: In metallic bonding, the metal ions are surrounded by a 'sea' of delocalised electrons that are free to move about.

Physical properties of metals

The key physical properties of metals can be explained using the model of metallic structure and bonding:

- Metals are good conductors of electricity. In an electrical circuit, metals can conduct electricity because the mobile electrons can move through the structure, carrying the current. This type of bonding is present in alloys as well. Alloys such as solder and brass, for example, will conduct electricity.
- Metals are easily bent and shaped (**malleable**). The positive ions in a metal are arranged in layers. When a force is applied, the layers can slide over each other. The attractive forces in metallic bonding act in all directions to hold the structure together. This means that when the layers slide over each other new bonds are easily formed (Figure C2.35). This movement of layers leaves the metal with a different shape.

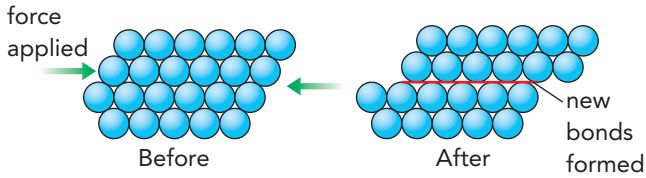

Figure C2.35: When a force is applied to a metal, the layers can slide over each other without breaking the structure.

KEY WORDS

'sea' of delocalised electrons: term used for the free, mobile electrons between the positive ions in a metallic lattice.

metallic bonding: an electrostatic force of attraction between the mobile 'sea' of electrons and the regular array of positive metal ions within a solid metal.

malleable: a word used to describe the property that allows metals to be bent and beaten into sheets.

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REFLECTION

This chapter involves drawing different diagrams and visual representations of molecules and structures. Do you find drawing these diagrams useful? Do these visualisations help you to understand the topic? Could you use diagrams in other topics in chemistry to help develop your understanding?

Diagrams can also be used to organise information. An example of this is Figure C2.36. How does this help you understand the links between the types of bonding we have discussed?

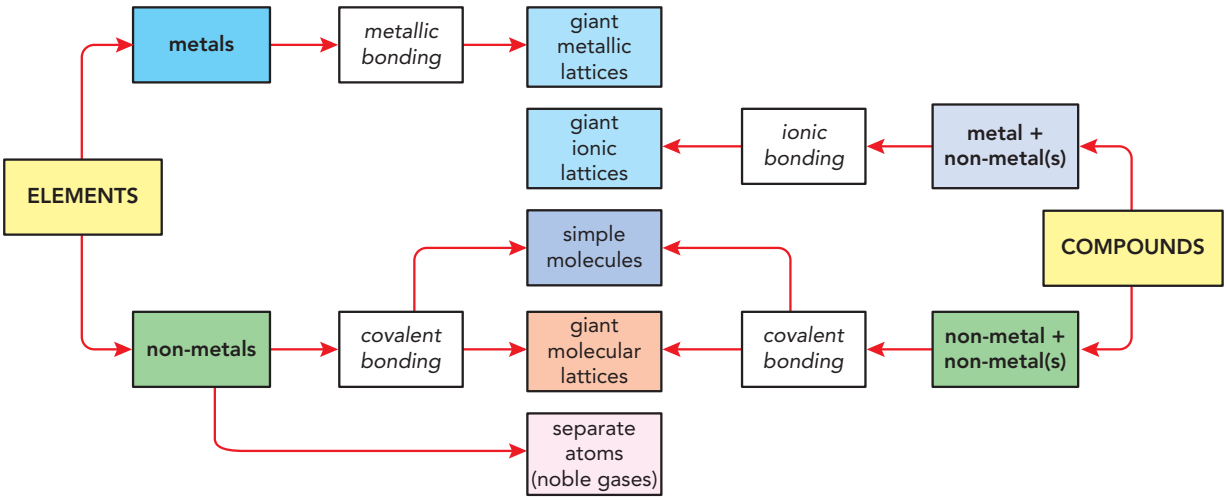

Figure C2.36: Summary of chemical bonding in elements and compounds.

Questions

C2.18 Which *one* of the following elements exists as a giant covalent structure?

- **A** carbon
- **B** iodine
- **C** helium
- **D** oxygen

C2.19 Metals such as copper are bonded together by the attraction between metal ions and a 'sea' of delocalised electrons surrounding them. Which of the properties of metals (A–C) is not explained by this type of bonding?

- **A** electrical conductivity
- **B** malleability
- **C** reaction with acids

ACTIVITY C2.03

Mind-mapping chemical bonding

The types of bonding and particles described in the mind map you devised in Activity C2.02 (Part 1) produce several different giant structures present in solid substances. Look back at the mind map you created and see how you can extend it to include these structures.

Peer assessment

Swap your mind map with a partner and use the following checklist to ask them questions:

- Have they completed the ideas about atomic theory?
- Have they included the key information on ionic bonding?
- Have they included the key ideas on covalent bonding?
- Have they made links between the different ideas in a different colour?
- Have they included ideas about giant structures?
- Were there ideas you could gain from looking at your partner's mind map?

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PROJECT C2.01 MODELLING THE STRUCTURE OF AN ATOM

You will have seen many different representations of atoms in the media. Often images show electrons orbiting like planets (Figure C2.37a). After completing this chapter, you will have learnt much more about atomic structure, and understand that electrons are arranged around a central nucleus in energy levels (Figure C2.37b).

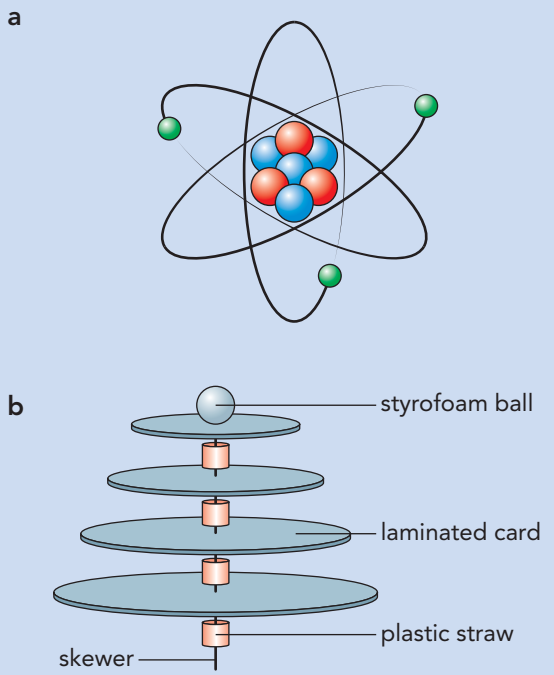


Figure C2.37 a: A planetary model of an atom showing three electrons orbiting a nucleus. **b:** Model of the electron energy levels in an atom.

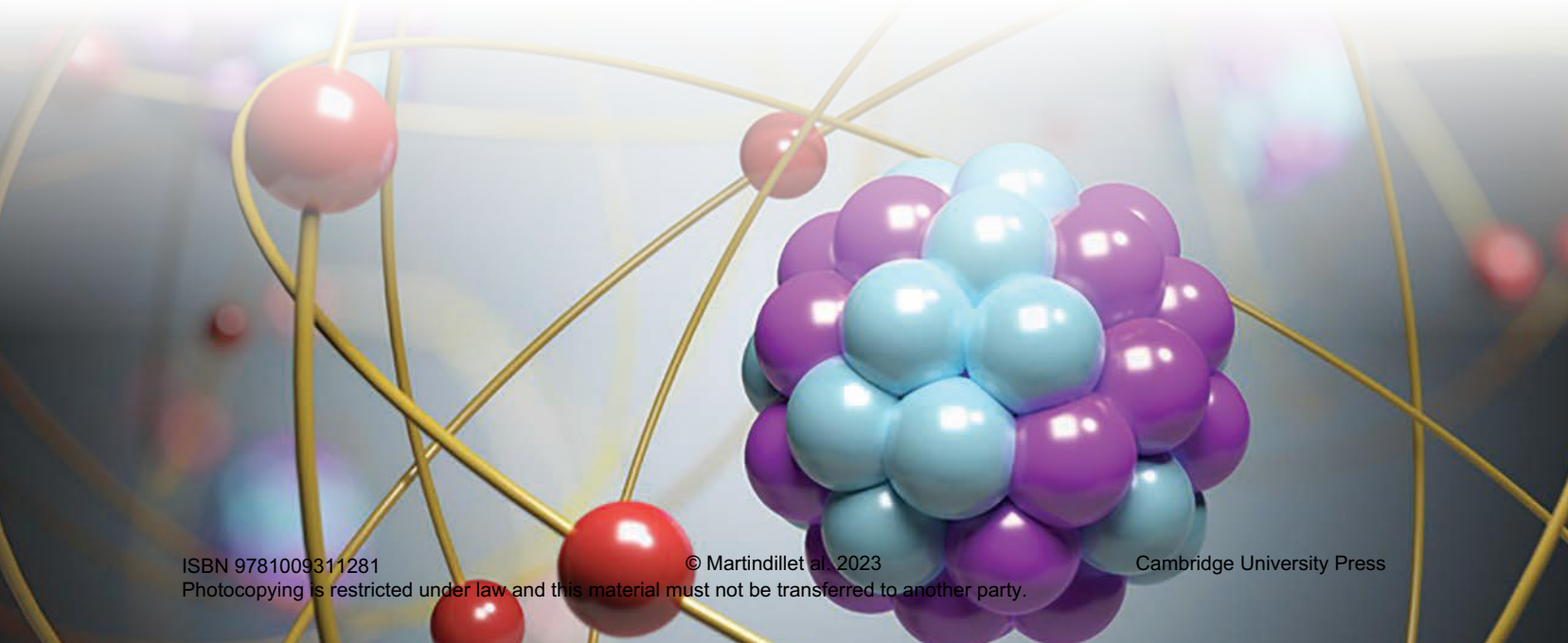
Now it is your turn to try to represent an atom by creating a 3D model.

Working in groups, construct a model of either:

- a planetary model of a simple atom, or
- a model showing the energy levels that electrons can occupy in an atom – representing the energy levels like trays with a certain number of electrons on each tray (see Figure C2.37 for the basis of such a model).

Having constructed your model, take a moment to assess how well it represents an atom. Be critical of your model and discuss the limitations of the model with your group.

How well does your model represent what you have learnt in this chapter?



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SUMMARY

The elements are the basic building units of the material world. They cannot be chemically broken down into anything simpler. They can be divided up into metals and non-metals.
There are differences between chemical elements, compounds and mixtures.
The atoms of the elements are made up of different combinations of the subatomic particles (protons, neutrons and electrons) and an element is made up of atoms that all have the same number of protons.
These subatomic particles have particular electrical charges and relative masses.
In any atom, the protons and neutrons are bound together in a central nucleus, and the electrons 'orbit' the nucleus in different energy levels (or shells).
The number of protons in an atom is defined as the proton (atomic) number (Z) of the element. The total number of protons and neutrons in an atom is defined as the mass (nucleon) number (A).
The electrons in atoms are arranged in different shells (or energy levels) that are at different distances from the nucleus of the atom.
Each shell (or energy level) has a maximum number of electrons that it can contain and the electrons fill the shells closest to the nucleus first.
Isotopes of the same element can exist and differ only in the number of neutrons in their nuclei.
The chemical properties of all the isotopes of an element are the same because they have the same electronic configuration.
A covalent bond is formed between two non-metal atoms by the sharing of outer electrons. This is illustrated using dot-and-cross diagrams.
Compounds combining metals and non-metals involve ionic bonding, and dot-and-cross diagrams show electron transfer.
An ionic bond is a strong electrostatic attraction between oppositely charged ions.
The physical properties of simple molecular compounds and ionic compounds can be related to their structure and bonding.
Diamond and graphite have giant covalent structures. These very strong structures make them useful and versatile.
Metals exhibit metallic bonding which gives rise to their properties.

PRACTICE QUESTIONS

1 The structure of an atom is defined by two numbers: the proton (atomic) number and the mass (nucleon) number. **Identify** the electronic configuration of an atom with proton number 5 and mass number 11.

A 2,8,1
B 3,2
C 2,3
D 1,8,2 **[1]**

COMMAND WORDS

identify: name/select/recognise.

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CONTINUED

2 Elements in the Periodic Table are arranged in order of their proton number.

a **Define** *proton number*. **[1]**

b Argon, proton number 18, has a larger mass number than potassium, proton number 19. **Explain** why this is, considering the mass and atomic numbers. **[2]**

c Copy and complete this table to **give** the properties of the three particles that make up atoms. **[5]**

Particle	Charge	Mass	Position in atom
proton	+		
neutron		1	in the nucleus
electron	–		

d Atom X has only two of the three particles listed in the table above. **State** which element Atom X is an atom of. **[1]**

e Argon and helium are both noble gases. Give *one* way in which their electron structures are similar. **[1]**

[Total: 10]

3 $^{12}_{6}C$ and $^{14}_{6}C$ are two isotopes of the element carbon.

a **Describe** how the structure of their atoms differs. **[3]**

b Carbon reacts with oxygen to produce carbon dioxide. Give the electronic configuration of an oxygen atom. **[1]**

c Germanium (A_r = 32) is an element in the same group as carbon.

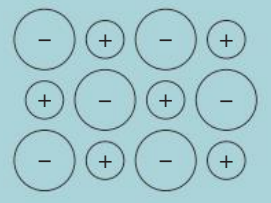
i State how many electrons germanium has in its outer electron shell. **[1]**

ii State which period of the Periodic Table germanium is found in. **[1]**

[Total: 6]

4 The element copper has two main isotopes $^{63}_{29}Cu$ and $^{65}_{29}Cu$. Both isotopes have the same chemical properties. Explain why the chemical properties of these two isotopes are the same. **[2]**

5 There are various different types of structure that compounds can form, depending on the nature of their bonding. A substance has an ionic structure that can be represented as shown in the figure below.



a **Suggest** what this substance could be.

A iodine

B water

C potassium bromide

D diamond **[1]**

b Give reasons for your answer to part **a**. **[2]**

[Total: 3]

COMMAND WORDS

define: give a precise meaning.

explain: set out purposes or reasons/ make the relationships between things clear/ say why and/or how and support with relevant evidence.

give: produce an answer from a given source or recall/ memory.

state: express in clear terms.

COMMAND WORD

describe: state the points of a topic/give characteristics and main features.

COMMAND WORD

suggest: apply knowledge and understanding to situations where there are a range of valid responses in order to make proposals/put forward considerations.

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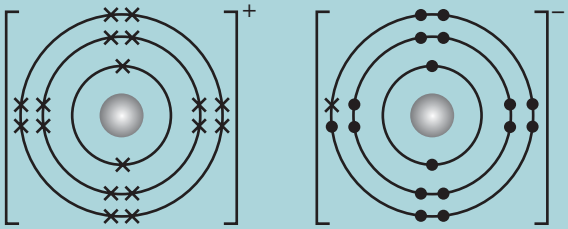
CONTINUED

6 When potassium reacts with chlorine the ionic compound potassium chloride is formed. The electronic configurations of the two ions formed are the same.



a Explain what has happened during the reaction to form these two ions. **[2]**

b When two chlorine atoms react with each other ions are not formed.

Sketch a dot-and-cross diagram to show the bond between two chlorine atoms. Show outer shell electrons only. **[2]**

c Give the name of this type of bond. **[1]**

d Give a difference in physical properties between chlorine and potassium chloride. **[1]**

[Total: 6]

7 Carbon exists in two forms, diamond and graphite. Both forms have very high melting points. Graphite conducts electricity but diamond does not.

a Explain why graphite has a high melting point and conducts electricity. **[2]**

b Graphite is soft and can be used as a lubricant, but diamond is very hard. Explain this difference. **[2]**

[Total: 4]

COMMAND WORDS

sketch: make a simple freehand drawing showing the key features, taking care over proportions.

SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
understand that matter is made up of elements and compounds	C2.01			
describe the difference between elements, compounds and mixtures	C2.01			
describe the structure of the atom as a central nucleus surrounded by electrons	C2.02			
define the properties of protons, neutrons and electrons, and the meaning of the proton (atomic) number and nucleon (mass) number of an atom	C2.02			
give the electronic configuration of a given atom	C2.02			

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CONTINUED

I can	See topic . . .	Needs more work	Almost there	Confident to move on
relate the electronic configuration of an element to its position in the Periodic Table	C2.02			
define isotopes as atoms of an element with the same proton number but different nucleon numbers, and use symbols for atoms and ions such as $^{35}_{17}Cl^-$	C2.03			
describe isotopes of an element as having the same chemical properties because they have the same electronic configuration	C2.03			
state that chemical bonding involves the outer electrons of the atoms involved	C2.04			
describe the formation of ionic bonds between the ions of Group I metals and Group VII halogens by electron transfer	C2.05			
describe the properties of ionic compounds	C2.05			
use dot-and-cross diagrams to show the structure of more complicated ionic compounds	C2.05			
explain some of the physical properties of ionic compounds	C2.05			
describe the giant lattice structures of ionic compounds as a regular arrangement of alternating positive and negative ions	C2.05			
describe how a covalent bond is formed when a pair of outer electrons are shared between two atoms, using dot-and-cross diagrams to illustrate the sharing of electrons	C2.06			
outline some of the properties of simple molecular compounds	C2.06			
explain how properties of simple molecular compounds relate to their structure and bonding	C2.06			
describe the giant molecular structures of diamond and graphite	C2.07			
describe the key properties of diamond and graphite	C2.07			
describe the bonding in metals and how this links to properties.	C2.08			

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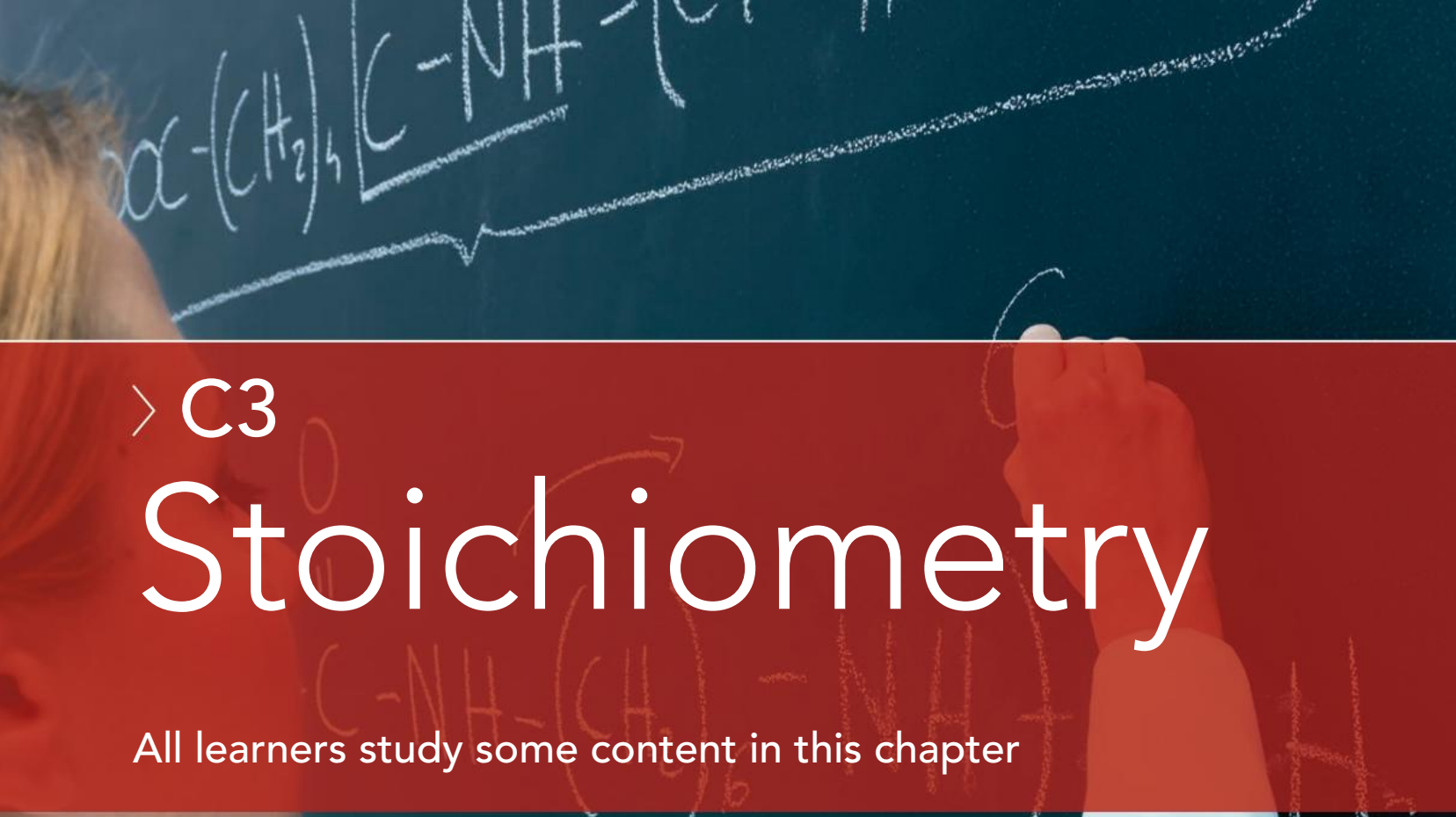

C3 Stoichiometry

All learners study some content in this chapter

IN THIS CHAPTER YOU WILL:

- identify that concentration can be measured in g/dm^3
- understand how to write the chemical formulae of elements and compounds
- define the molecular formula as the number and type of different atoms in one molecule
- deduce the formula of simple covalent compounds
- explore how to write and use word equations
- interpret and balance symbol equations
- construct and use symbol equations, with state symbols, including ionic equations
- deduce the formula of an ionic compound
- deduce the balanced equation for a chemical reaction, given relevant information
- describe the relative atomic mass (A_r) and understand how to use A_r to calculate the relative molecular (or formula) mass (M_r)
- calculate reacting masses using proportions
- define the terms mole and Avogadro's constant
- understand how to use the equation $\text{amount (number of moles)} = \frac{\text{mass (in g)}}{\text{molar mass (in g/mol)}}$ to calculate amount of substance, mass, molar mass and relative atomic mass or relative molecular/formula mass
- carry out mole calculations for gases (using the molar gas volume), reacting masses and solutions using concentrations, including using the idea of limiting reagents.

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BEFORE YOU START

Knowledge of the symbols of the elements and their use in chemical formulae is important in building confidence in chemistry.

- Think about the symbols of elements and any formulae of compounds you have met when learning science: write a list of as many as you can think of.
- Based on this list, create five questions to ask a partner.
- Working in pairs, take it in turns to ask each other your questions.

How did you do? Discuss with your partner what you know about the elements and formulae included in your questions.

SCIENCE IN CONTEXT C3.01

Chemical accountancy

The rather unusual word stoichiometry is derived from two Greek words – *stoicheion* (meaning element), and *metron* (meaning measure). It describes the relative measures, or amounts, of a reactant and a product in a chemical reaction. Chemists talk of stoichiometry when they balance symbol equations, and it is how they work out what quantities of different substances will react to form particular amounts of product. You can think of stoichiometry as the link between what happens at an atomic level and what can be measured practically in a reaction. Although the pairing of elements may change in a chemical reaction, the amount of matter remains the same, so stoichiometry is a type of chemical accountancy that takes place at the atomic level. The standard amount of substance that contains a known number of particles at an atomic level is known as the mole.

The concept of the mole is important to new developments in industrial chemistry, where the 12 principles of *Green Chemistry* have been proposed to guide more sustainable chemical engineering. Green Chemistry emphasises that industrial processes should reduce the use, or production, of hazardous or waste substances (Figure C3.01). Reducing the involvement of hazardous substances makes the environmental safety of any new process more effective.

Figure C3.01: Modern chemical plants should be designed for safety and atom economy.

Discussion questions

1 What costs, other than those of the raw materials, should be considered when considering the economy of an industrial process?

2 In what way could the economic problem of by-products be reduced by positive and imaginative marketing?

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C3.01 Chemical formulae and equations

Formulae of elements

When we were discussing the difference between elements and compounds in Chapter C2, we briefly commented that each element has its own **chemical symbol** which is shown in the Periodic Table. All chemical symbols are either a single capital letter, such as hydrogen (H), oxygen (O) and nitrogen (N), or made up of two letters, such as aluminium (Al), argon (Ar) or magnesium (Mg). It is important to remember that the second letter of any symbol is always a small (lower case) letter. For some elements the symbol is taken from the Latin name of the element (Table C3.01).

Element	Latin name	Chemical symbol
silver	argentum	Ag
gold	aurum	Au
copper	cuprum	Cu
sodium	natrium	Na
potassium	kalium	K
iron	ferrum	Fe
lead	plumbum	Pb

Table C3.01: Latin names and chemical symbols for some important elements.

The use of symbols means that we can quickly represent an element and its structure. For the elements whose structures are made up of individual atoms (the noble gases), the formula of the element is simply its symbol (Figure C3.02).

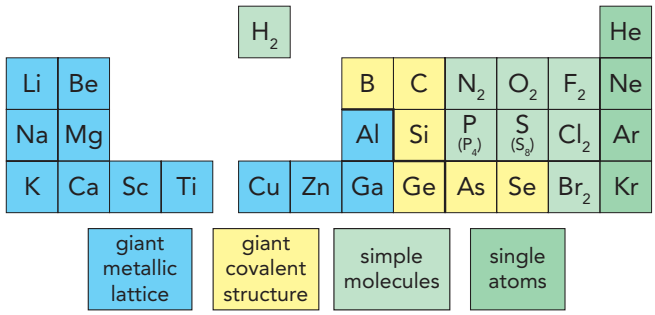

Figure C3.02: Formulae of the elements reflect their structure and position in the Periodic Table.

Where elements exist as giant structures, whether held together by metallic or covalent bonding, the formula is simply the symbol of the element (e.g. Cu, Mg, Fe, Na, K, C, Si, Ge). For molecular species, the formula represents the atoms present in the molecule.

Formulae of compound ions

The ionic compounds mentioned in earlier chapters are all composed of two simple ions bonded together (e.g. Na^+, K^+, Mg^{2+}, Cl^-, O^{2-}). However, in many important ionic compounds the metal ion is combined with a negative ion containing a group of atoms (e.g. SO_4^{2-}, NO_3^-, CO_3^{2-}). These **compound ions**, or charged groups, are made up of atoms covalently bonded together. They have a negative charge because they have gained electrons to make a stable structure. Examples of such ions are shown in Figure C3.03. In addition to these negative compound ions, there is one important compound ion that is positively charged, the ammonium ion, NH^{4+} (Figure C3.03).

KEY WORDS

chemical symbol: a letter or group of letters representing an element in a chemical formula.

compound ion: an ion made up of several different atoms covalently bonded together and with an overall charge (can also be called a molecular ion; negatively charged compound ions containing oxygen can be called oxyanions).

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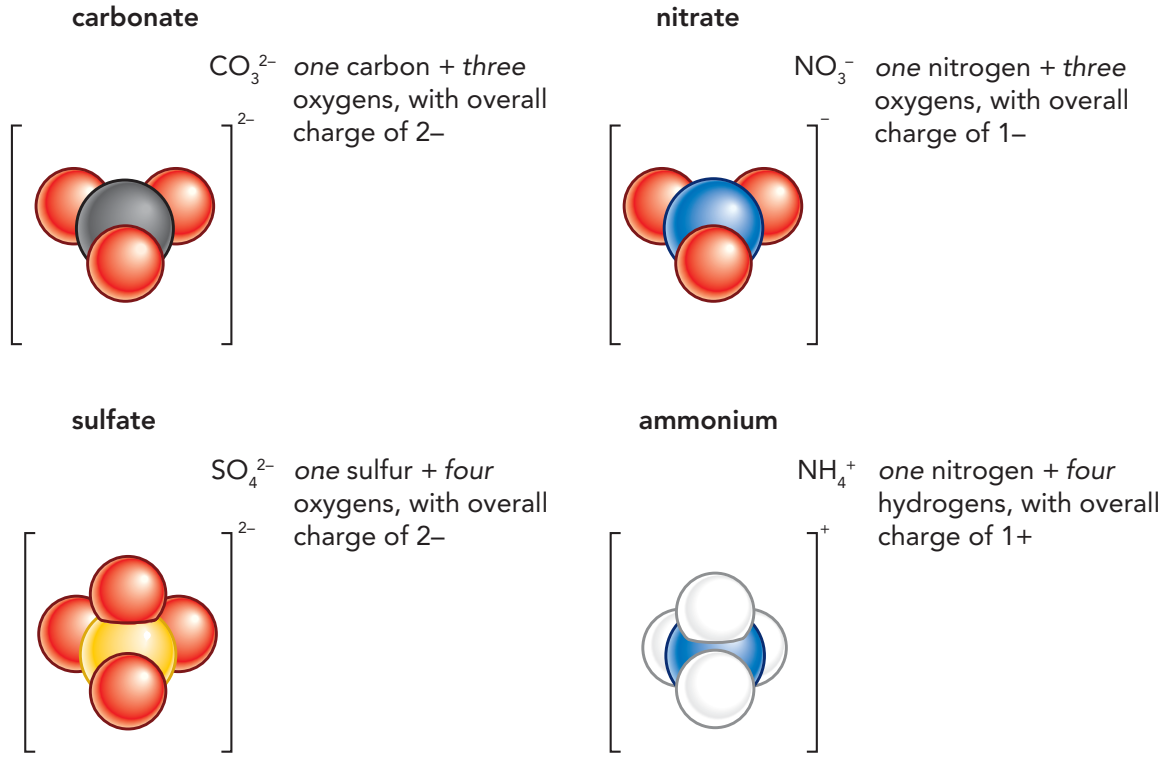

Figure C3.03: Three examples of negatively charged compound ions and a positively charged compound ion. The numbers of atoms and the overall charge carried by each group of atoms are shown. Compound ions are drawn in square brackets with the charge outside the brackets to show that the charge is spread over the whole ion.

Formulae of compounds

Formulae of simple covalent compounds

Atoms of each element have a combining power, sometimes referred to as their *valency*. The combining power of an atom in a covalent molecule is the number of bonds that atom makes. This idea of an atom having a valency can be used to work out the formulae of covalent compounds. Note that the term valency is not required knowledge.

The valency of an element in the main groups of the Periodic Table can be deduced from the group number of the element. The relationship between valency and group number is:

- For elements in Groups I–IV valency = group number.
- For elements in Groups V–VII valency = 8 – the group number.
- For elements in Group VIII valency = 0.

The 'cross-over' method for working out chemical formulae can be applied to simple covalent compounds where the molecules have a central atom, e.g. water, methane, carbon dioxide and ammonia (Worked example C3.01).

Group	I	II	III	IV	V	VI	VII	VIII
Valency (combining power)	1	2	3	4	3	2	1	0
Typical compound	NaCl	$MgCl_2$	$AlCl_3$	$SiCl_4$	PH_3	H_2S	HCl	—

Table C3.02: Typical compounds of the elements of Period 3 showing the change in valency across the period.

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WORKED EXAMPLE C3.01

Work out the formula of carbon dioxide.

Use a method involving the symbols and valencies of the elements:

Step 1: Write down the symbols of the elements.

Step 2: Write the valencies of the elements beneath their symbols (Figure C3.04).

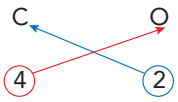
Step 3: 'Cross over' to give the ratio of atoms present in the formula.

Step 4: If necessary, simplify the ratio.

Formula of carbon dioxide

Write down the symbols

Write down the valencies



C_2O_4

Can simplify:

Formula **CO_2**

Figure C3.04: A method for finding the formula of carbon dioxide.

If we are given a diagram of a molecule showing all the atoms and bonds, we can easily work out its **molecular formula**. We do this by simply counting the number of each type of atom present. Figure C3.05 shows diagrams of molecules with the molecular formulae BrF_3, NH_3 and C_3H_6.

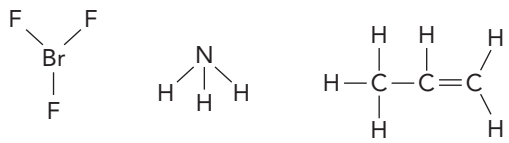


Figure C3.05: Diagrams showing the structures of BrF_3, NH_3 and C_3H_6.

KEY WORDS

molecular formula: a formula that shows the actual number of atoms of each element present in a molecule of the compound.

Formulae of ionic compounds

Ionic compounds have giant ionic lattice structures (Chapter C2) and their formulae are simply the whole number ratio of the positive to negative ions in the structure. The overall structure must be neutral.

The positive and negative charges must balance each other and the cross-over method can be used to work these formulae out. Thus, in magnesium chloride we have:

ions present	Mg^{2+}	$2Cl^-$
total charge	2+	2–

There are two chloride ions (Cl^-) for each magnesium ion (Mg^{2+}). The chemical formula is $MgCl_2$.

The size of the charge on an ion is a measure of its valency (Table C3.02). Mg^{2+} ions can combine with Cl^- ions in a ratio of 1:2, but Na^+ ions can only bond in a 1:1 ratio with Cl^- ions.

We can adapt the rules as above to work out the charge:

- Metals and hydrogen will be positively charged and non-metals will be negatively charged.
- For elements in Groups I–IV, charge = group number.
- For elements in Groups V–VII, charge = 8 – the group number.
- For transition elements, which can have variable oxidation states, the charge is given by the number in brackets within the name, e.g. copper(I) has a 1+ charge and Cu(II) has a 2+ charge.

Follow the examples of aluminium oxide and calcium oxide in Figure C3.06 (Worked example C3.02), and make sure you understand how this works.

WORKED EXAMPLE C3.02

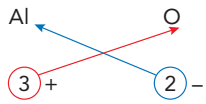
Work out the formulae of aluminium oxide and calcium oxide.

Formula for aluminium oxide

Write down the correct symbols

Write down the charges on the ions

cross over the charges to give the number of the opposite atom present



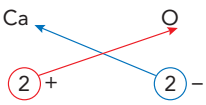
Formula **Al_2O_3**

Formula for calcium oxide

Write down the correct symbols

Write down the charges on the ions

cross over the charges to give the number of the opposite atom present



Ca_2O_2

Simplify the ratio:

Formula **CaO**

Figure C3.06: Working out the formulae of aluminium oxide and calcium oxide.

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The same rules apply when writing the formulae of compounds containing compound ions because each of them has an overall charge (Table C3.03). It is useful to put the formula of the compound ion in brackets, showing that the formula of this ion cannot be changed (Figure C3.07).

For example, the formula of the carbonate ion is always CO_3^{2-}. Worked example C3.03 shows how the formulae for sodium carbonate and ammonium sulfate can be determined.

Table C3.03 summarises the formulae of some important ionic compounds.

Name	Formula	Ions present		Ratio
sodium chloride	$NaCl$	Na^+	Cl^-	1 : 1
ammonium nitrate	NH_4NO_3	NH_4^+	NO_3^-	1 : 1
potassium sulfate	K_2SO_4	K^+	SO_4^{2-}	2 : 1
calcium hydrogencarbonate	$Ca(HCO_3)_2$	Ca^{2+}	HCO_3^-	1 : 2
copper(II) sulfate	$CuSO_4$	Cu^{2+}	SO_4^{2-}	1 : 1
magnesium nitrate	$Mg(NO_3)_2$	Mg^{2+}	NO_3^-	1 : 2
aluminium chloride	$AlCl_3$	Al^{3+}	Cl^-	1 : 3

Table C3.03: Formulae of some ionic compounds.

WORKED EXAMPLE C3.03

Work out the formulae of sodium carbonate and ammonium sulfate.

Formula of sodium carbonate

Write down the correct symbols — Na (CO$_3$)

Write down the charges on the ions — 1 + 2 –

Formula **Na_2CO_3**

The brackets are not needed if there is only one ion present

Formula of ammonium sulfate

Write down the correct symbols — (NH$_4$) (SO$_4$)

Write down the charges on the ions — 1 + 2 –

Formula **$(NH_4)_2SO_4$**

Figure C3.07: Working out the formulae of sodium carbonate and ammonium sulfate.

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ACTIVITY C3.01

Jigsaw compounds

Work in groups to make a set of jigsaw cards for the common ions that form compounds (Figure C3.08).

You will need:
- paper
- scissors
- pens.

Step 1: Use the selection of ionic compounds and ions in Table C3.03.

Step 2: In order for the jigsaw pieces to make a compound, the shapes need to fit together to make a rectangle. On a piece of paper, draw seven rectangles to represent the seven compounds.

Step 3: Divide each rectangle into cards representing the ions needed for each compound. For the positive ions, create 'slots' in the card. For the negative ions, create 'tabs'. The 'tabs' on the negative ions should fit into the 'slots' in the positive ion cards. The number of slots or tabs on each card represents the charge of the ion. Use Figure C3.08 as a guide. More than one card of the same ion may be needed to complete the compound. In addition to the cards based on the ions in Table C3.03 you should make cards for CO_3^{2-}, O^{2-} and Fe^{3+} ions (see Figure C3.08).

Step 4: Make sure each card is labelled with the formula of the ion it represents. Then your rectangle of cards will give you the formula of the ionic compound concerned.

Step 5: Cut out your cards to be used as a jigsaw.

- Having made your set of cards, use them to work out the formulae of the following compounds: copper carbonate, iron(III) oxide and ammonium sulfate.
- Then challenge each other in the group to make a compound you name.
- Using some of your examples, compare this method to the cross-over method described earlier in this chapter.

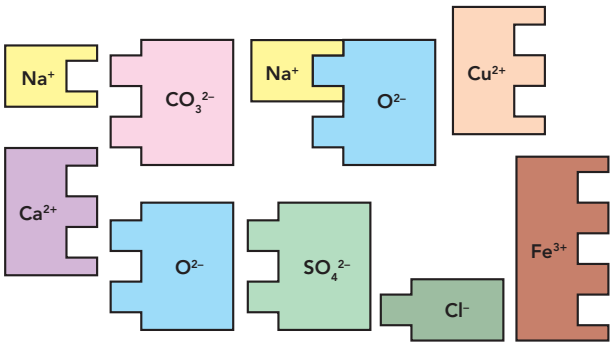

Figure C3.08: Examples of jigsaw cards designed to help with matching ionic charge to form compounds.

Self assessment

Think about the following questions, and give yourself a ☺ 😐 or ☹.

How confident did you feel . . .

- working out and writing the formulae of ionic compounds?
- working out the formula of copper carbonate?
- working out the formula of iron(III) oxide?
- working out the formula of ammonium sulfate?

Do you find this method of finding the formula of an ionic compound more helpful than the cross-over method?

Chemical equations for reactions

When some chemical reactions occur, it is obvious that 'something has happened'. But this is not the case for others. When a solid explosive reacts to produce large amounts of gas products, the rapid expansion may blast the surroundings apart.

The 'volcano reaction', in which ammonium dichromate is decomposed, gives out a large amount of energy and produces nitrogen gas (Figure C3.09). Other reactions produce gases much less violently. The neutralisation of an acid solution with an alkali produces no change that you can see. However, a reaction has happened.

Word equations

We can write out descriptions of chemical reactions, but these would be quite long. To understand and group similar reactions together, it is useful to have a shorter way of describing them. The simplest way to do this is in the form of a **word equation**.

KEY WORDS

word equation: a summary of a chemical reaction using the chemical names of the reactants and products.

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Figure C3.09: Decomposition of ammonium dichromate (the 'volcano experiment') produces heat, light and an apparently large amount of powder.

This type of equation links together the names of the substances that react (**reactants**) with those of the new substances formed (**products**). The word equation for burning magnesium in oxygen would be:

magnesium + oxygen → magnesium oxide
reactants product

The reaction between hydrogen and oxygen is another highly exothermic reaction. The hydrogen–oxygen fuel cell is based on this reaction (Chapter C4). The word equation for this reaction is:

hydrogen + oxygen → water

Note that, although a large amount of energy is produced in this reaction, it is not included in the equation. An equation includes only the chemical substances involved, and energy is not a chemical substance.

This type of equation gives us some information. But equations can be made even more useful if we write them using chemical formulae.

KEY WORDS

reactants (in a chemical reaction): the chemical substances that react together in a chemical reaction.

products (in a chemical reaction): the substance(s) produced by a chemical reaction.

Balanced symbol equations

The law of conservation of mass states that the total mass of all the products of a chemical reaction is always equal to the total mass of all the reactants. During a chemical reaction, the atoms of one element are not changed into those of another element. Atoms do not disappear from the mixture or appear from nowhere. A reaction involves the breaking of some bonds between atoms, and then the making of new bonds between some of these same atoms to give the new products.

Look more closely at the reaction between hydrogen and oxygen molecules shown in Figure C3.10.

hydrogen + oxygen → water

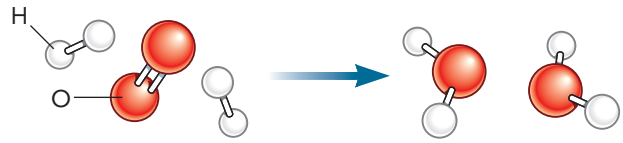

Figure C3.10: A chemical reaction involves atoms breaking and forming bonds and new substances being formed.

Each molecule of water (H_2O) contains only one oxygen atom (O). It follows that one molecule of oxygen (O_2) has enough oxygen atoms to produce two molecules of water (H_2O). Therefore, two molecules of hydrogen (H_2) will be needed to provide the four hydrogen atoms (H) needed to react with the oxygen molecule. The numbers of hydrogen and oxygen atoms are the same on both sides of the equation (Figure C3.11).

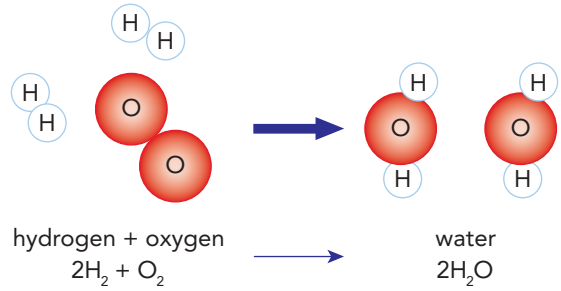

Figure C3.11: Summary of the reaction between hydrogen and oxygen.

The symbol equation for the reaction between hydrogen and oxygen is therefore written:

$$2H_2 + O_2 \rightarrow 2H_2O$$

The number 2 in front of the H_2 and H_2O shows that we have two molecules of hydrogen and water in the reaction for each one oxygen molecule present (note, when no number is present in front of a molecular formula, we presume that there is one of that species present).

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This is a **balanced chemical equation**.

KEY WORDS

balanced chemical equation: a summary of a chemical reaction using chemical formulae; the total number of any of the atoms involved is the same on both the reactant and product sides of the equation.

A balanced equation gives us more information about a reaction than we can get from a simple word equation.

When we balance an equation, we cannot alter the formulae of the elements and compounds involved in the reaction. These are fixed by the bonding in the substance itself. We can only put multiplying numbers in front of each formula where necessary.

For example, potassium reacts with water to produce potassium hydroxide and hydrogen (Figure C3.12).

Figure C3.12: Potassium reacts strongly with water to produce hydrogen and potassium hydroxide.

All the Group I metals react with water in the same way. So, if you know one of these reactions, you know them all (these will be covered in more detail in Chapter C9). The general equation is:

alkali metal + water → metal hydroxide + hydrogen

Therefore:

potassium + water → potassium hydroxide + hydrogen

Then we work out the formula for each substance present:

$$K + H_2O \rightarrow KOH + H_2$$

This symbol equation needs to be balanced. This means we have to work out how many of each element/molecule we have present. We need to make sure there are the same number of each type of atom present on the reactant and product sides of the equation. Remember, we do not have to have a 1 : 1 ratio. In this example, we must have an even number of hydrogen atoms on the product side as, on the reactant side, the hydrogen occurs only as H_2O (the hydrogens must come in pairs). Therefore, the amount of KOH must be doubled. Then the number of potassium atoms and water molecules must be doubled on the left:

$$2K + 2H_2O \rightarrow 2KOH + H_2$$

This equation is now balanced. Check for yourself that the numbers of the three types of atoms are the same on both sides.

Worked example C3.04 shows a step-by-step approach to working out the balanced equation for a reaction.

WORKED EXAMPLE C3.04

What is the balanced equation for the reaction between magnesium and oxygen?

Step 1: Make sure you know what the reactants and products are. For example, magnesium burns in air (oxygen) to form magnesium oxide.

Step 2: From this you can write out the word equation:

magnesium + oxygen → magnesium oxide

Step 3: Write out the equation using the formulae of the elements and compounds:

$Mg + O_2 \rightarrow MgO$

Remember that oxygen exists as diatomic molecules. This equation is not balanced: there are two oxygen atoms on the left, but only one on the right.

Step 4: Balance the equation:

$2Mg + O_2 \rightarrow 2MgO$

Now work through the steps to find the balanced symbol equation for the reaction that takes place when burning sodium is lowered into a gas jar of chlorine gas. Sodium chloride is produced in this reaction. Remember that chlorine is a diatomic gas.

Questions

C3.01 Write word equations for the reactions described in **a–c**.

a Iron rusts because it reacts with oxygen in the air to form a compound called iron(III) oxide.

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b Sodium hydroxide neutralises sulfuric acid to form sodium sulfate and water.

c Sodium reacts strongly with water to give a solution of sodium hydroxide; hydrogen gas is also given off.

C3.02 Balance the following symbol equations:

a ____$Cu + O_2 \rightarrow$ ____CuO

b $N_2 +$ ____$H_2 \rightarrow$ ____NH_3

c ____$Na + O_2 \rightarrow$ ____Na_2O

d ____$NaOH + H_2SO_4 \rightarrow Na_2SO_4 +$ ____H_2O

e ____$Al +$ ____$Cl_2 \rightarrow$ ____$AlCl_3$

f ____$Fe +$ ____$H_2O \rightarrow$ ____$Fe_3O_4 +$ ____H_2

C3.03 Use these word equations to write balanced symbol equations.

a hydrogen + chlorine → hydrogen chloride

b copper + oxygen → copper oxide

c magnesium + zinc chloride → magnesium chloride + zinc

Using state symbols

So far, our equations have told us nothing about the physical state of the reactants and products. Chemical equations can be made more useful by including symbols that give us this information. These are called **state symbols**. They show clearly whether a gas is given off or a solid precipitate is formed during a reaction. The four symbols used are shown in Table C3.04.

Symbol	Meaning
s	solid
l	liquid
g	gas
aq	aqueous solution (dissolved in water)

Table C3.04: State symbols used in chemical equations.

The examples A–C show how state symbols can be included in a symbol equation. Note that when water itself is produced in a reaction, it has the symbol (l) for liquid, not (aq).

A magnesium + nitric acid → magnesium nitrate + hydrogen

$Mg(s) + 2HNO_3(aq) \rightarrow Mg(NO_3)_2(aq) + H_2(g)$

B hydrochloric acid + sodium hydroxide → sodium chloride + water

$HCl(aq) + NaOH(aq) \rightarrow NaCl(aq) + H_2O(l)$

C copper(II) sulfate + sodium hydroxide → copper(II) hydroxide + sodium sulfate

$CuSO_4(aq) + 2NaOH(aq) \rightarrow Cu(OH)_2(s) + Na_2SO_4(aq)$

Ionic equations

Equations **B** and **C** in the previous topic involve mixing solutions that contain ions. Only some of the ions present actually change their status. They do this by changing either their bonding or their physical state. The other ions present are simply *spectator ions*; they do not change during the reaction. Note that use of this term is not specifically required at this level.

The neutralisation of hydrochloric acid with sodium hydroxide solution can be represented by:

$$HCl(aq) + NaOH(aq) \rightarrow NaCl(aq) + H_2O(l)$$

Writing out all the ions present, we get:

$$[H^+(aq) + \cancel{Cl^-(aq)}] + [\cancel{Na^+(aq)} + OH^-(aq)] \rightarrow [\cancel{Na^+(aq)} + \cancel{Cl^-(aq)}] + H_2O(l)$$

The use of state symbols clearly shows which ions have not changed during the reaction. They have been crossed out (~~like this~~) and can be left out of the equation. This leaves us with the essential **ionic equation** for all neutralisation reactions:

$$H^+(aq) + OH^-(aq) \rightarrow H_2O(l)$$

Applying the same principles to a precipitation reaction again gives us a clear picture of which ions are reacting (Figure C3.13).

The equation:

$$CuSO_4(aq) + 2NaOH(aq) \rightarrow Cu(OH)_2(s) + Na_2SO_4(aq)$$

for the precipitation of copper(II) hydroxide can be written with the ions separated:

$$Cu^{2+}(aq) + (SO_4)^{2-}(aq) + 2Na^+(aq) + 2OH^-(aq) \rightarrow Cu(OH)_2(s) + 2Na^+(aq) + (SO_4)^{2-}(aq)$$

removing the spectator ions, this becomes:

$$Cu^{2+}(aq) + 2OH^-(aq) \rightarrow Cu(OH)_2(s)$$

KEY WORDS

state symbols: symbols used to show the physical state of the reactants and products in a chemical reaction.

ionic equation: the simplified equation for a reaction involving ionic substances: only those ions which change during the reaction are shown.

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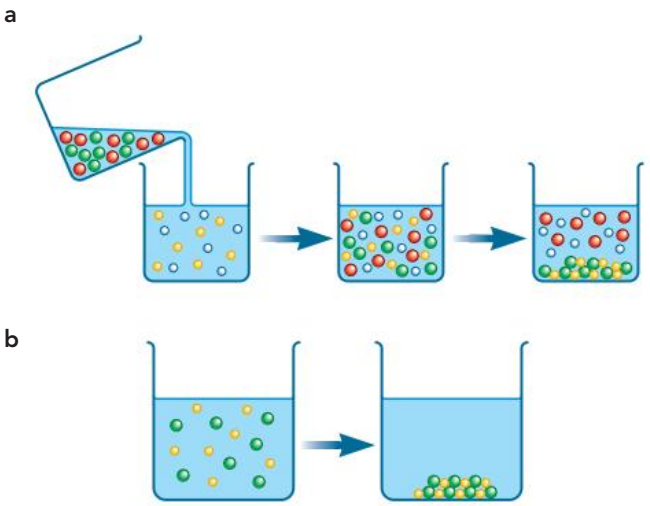

Figure C3.13: A precipitation reaction in which two solutions containing ions are mixed: **a:** the overall reaction, and **b:** the reaction with the spectator ions not shown.

Questions

C3.04 Explain the meaning of the symbols (s), (l), (aq) and (g) in the following equation, with reference to each reactant and product:

$Na_2CO_3(s) + 2HCl(aq) \rightarrow 2NaCl(aq) + H_2O(l) + CO_2(g)$

C3.05 Write an ionic equation, including state symbols, for each of the following reactions. (Note, you will have to initially construct a balanced symbol equation.)

a silver nitrate solution + sodium chloride solution → silver chloride + sodium nitrate solution

b sodium sulfate solution + barium nitrate solution → sodium nitrate solution + barium sulfate

C3.06 Write full symbol equations for the following reactions, followed by the ionic equation for the reaction (include state symbols in both types of equation).

a dilute hydrochloric acid + potassium hydroxide solution → potassium chloride solution + water

b dilute hydrochloric acid + copper carbonate → copper chloride solution + water + carbon dioxide

C3.02 Relative masses of atoms and molecules

Relative atomic mass of elements

The mass of a single hydrogen atom is incredibly small when measured in grams (g):

$$\text{mass of one hydrogen atom} = 1.7 \times 10^{-24}\,\text{g}$$
$$= 0.000\,000\,000\,000\,000\,000\,000\,001\,7\,\text{g}$$

It is much more useful and convenient to measure the masses of atoms relative to each other. To do this, a standard atom has been chosen, against which all others are then compared.

This standard atom is an atom of the carbon-12 isotope. The 'mass' of this isotope is given the value of exactly 12 (Figure C3.14).

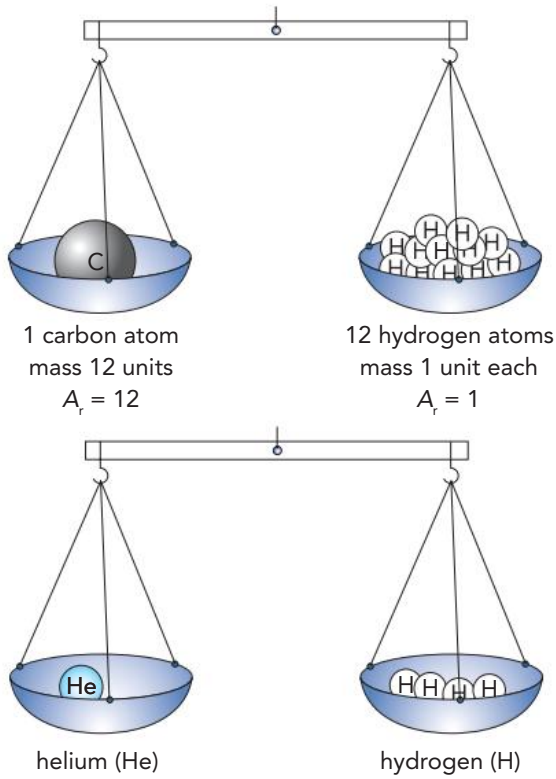

Figure C3.14: Relative mass of atoms. Twelve hydrogen atoms have the same mass as one atom of carbon-12. A helium atom has the same mass as four hydrogen atoms.

Remember from Chapter C2 that isotopes are atoms of the same element that have different masses because they have different numbers of neutrons in the nucleus. The majority of elements have several isotopes (Figure C3.15).

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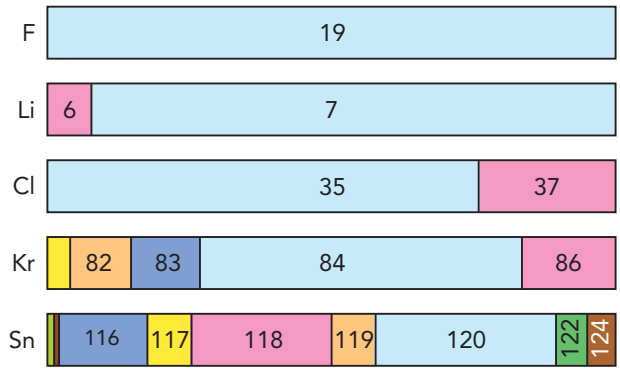

Figure C3.15: Many different elements have more than one isotope. These bars show the proportions of different isotopes for some elements. Fluorine is rare in having just one isotope.

As the mass of the isotopes of an atom differ slightly, the relative atomic mass of an element is the average mass of an atom of the element, taking into account the different natural isotopes of that element. This means that most relative atomic masses are not whole numbers (in this book and the Periodic Table used, with the exception of chlorine, they are rounded to the nearest whole number to make our calculations easier).

It is important to note that the mass of an ion will be the same as that of the parent atom. The mass of the electron(s) gained or lost in forming the ion can be ignored in comparison to the total mass of the atom.

Molecular (formula) mass of compounds

Atoms combine to form molecules or groups of ions. The total masses of these molecules or groups of ions provide useful information on the way the elements have combined with each other. To calculate the **relative molecular mass (M_r)** (or **relative formula mass (M_r)**), in the case of a giant ionic or covalent compound), the masses of the atoms or ions in the formula are added together. Here we illustrate the method by calculating the relative molecular masses of three simple substances.

Hydrogen gas is made up of H_2 molecules (H–H). Each molecule contains two hydrogen atoms. So, its relative molecular mass is twice the relative atomic mass of hydrogen:

$$M_r(H_2) = 2 \times 1 = 2$$

Water is a liquid made up of H_2O molecules (H–O–H). Each molecule contains two hydrogen atoms and one oxygen atom. So, its relative molecular mass is twice the relative atomic mass of hydrogen plus the relative atomic mass of oxygen:

$$M_r(H_2O) = (2 \times 1) + 16 = 18$$

Sodium chloride is an ionic solid. It contains one chloride ion for each sodium ion present. The **formula unit** of sodium chloride is Na^+Cl^-. So, its relative formula mass is the relative atomic mass of sodium plus the relative atomic mass of chlorine:

$$M_r(NaCl) = 23 + 35.5 = 58.5$$

The practical result of these definitions can be seen by looking at further examples (Table C3.05).

KEY WORDS

relative molecular mass (M_r): the sum of all the relative atomic masses of the atoms present in a molecule.

relative formula mass (M_r): the sum of all the relative atomic masses of the atoms present in a 'formula unit' of a substance.

formula unit: this unit of an element or compound is the molecule or group of ions defined by the chemical formula of the substance.

Compound formation and chemical formulae

The idea that compounds are made up of elements combined in fixed amounts can be shown experimentally. Samples of the same compound made in different ways always contain the same elements and the masses of the elements present are always in the same ratio.

Several different groups in a class can prepare magnesium oxide by heating a coil of magnesium in a crucible (Figure C3.16). The crucible must first be weighed empty, and then re-weighed with the magnesium in it. The crucible is then heated strongly. Air is allowed in by occasionally lifting the lid very carefully but solid must not be allowed to escape as a white smoke. The crucible and products are then allowed to cool before re-weighing.

The increase in mass that is observed is due to the oxygen that has now combined with the magnesium. The mass of magnesium used and the mass of magnesium oxide produced can be found from the results (Worked example C3.05).

The results of the various experiments in the class can be plotted on a graph. The mass of oxygen combined with the magnesium (y-axis) is plotted against the mass of magnesium used (x-axis). Figure C3.17 shows some results obtained from this experiment.

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Substance	Formula	Atoms in formula	Relative atomic masses, A_r			Relative molecular (or formula) mass, M_r		
hydrogen	H_2	2H	H	=	1	2 × 1	=	**2**
carbon dioxide	CO_2	1C	C	=	12	1 × 12	=	**12**
		2O	O	=	16	2 × 16	=	**32**
								44
calcium carbonate	$CaCO_3$ (one Ca^{2+} ion, one CO_3^{2-} ion)	1Ca	Ca	=	40	1 × 40	=	**40**
		1C	C	=	12	1 × 12	=	**12**
		3O	O	=	16	3 × 16	=	**48**
								100
ammonium sulfate	$(NH_4)_2SO_4$ (two NH_4^+ ions, one SO_4^{2-} ion)	2N	N	=	14	2 × 14	=	**28**
		8H	H	=	1	8 × 1	=	**8**
		1S	S	=	32	1 × 32	=	**32**
		4O	O	=	16	4 × 16	=	**64**
								132
hydrated magnesium sulfate	$MgSO_4 \cdot 7H_2O$ (one Mg^{2+} ion, one SO_4^{2-} ion, seven H_2O molecules)	1Mg	Mg	=	24	1 × 24	=	**24**
		1S	S	=	32	1 × 32	=	**32**
		4O	O	=	16	4 × 16	=	**64**
		14H	H	=	1	14 × 1	=	**14**
		7O	O	=	16	7 × 16	=	**112**
								246

Table C3.05: Relative formula masses of some elements and compounds.

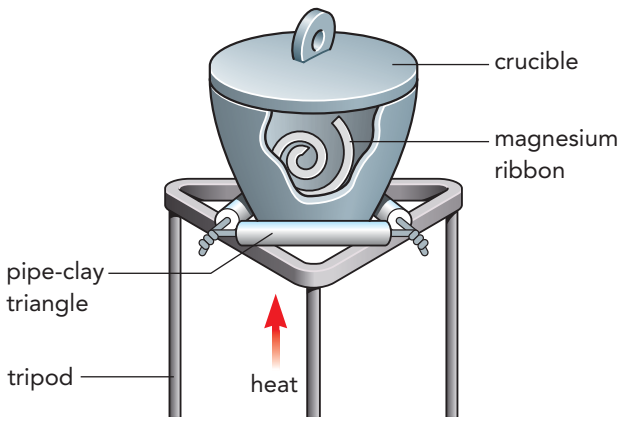

Figure C3.16: Heating magnesium in a crucible.

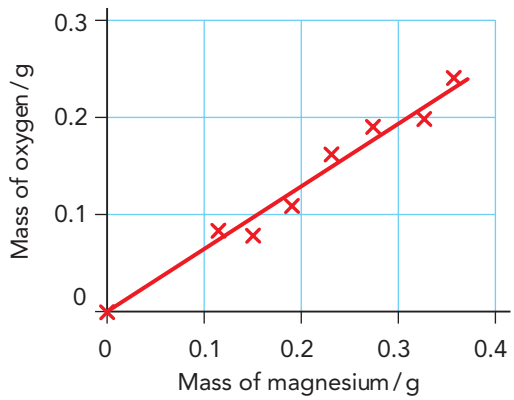

Figure C3.17: Graph of the results obtained from heating magnesium in air. The graph shows the mass of oxygen (from the air) that reacts with various masses of magnesium.

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WORKED EXAMPLE C3.05

How much magnesium oxide is produced from a given mass of magnesium?

Here are some results obtained from this experiment:

a mass of empty crucible + lid = 8.52 g

b mass of crucible + lid + magnesium = 8.88 g

c mass of crucible + lid + magnesium oxide = 9.12 g

d mass of magnesium (b − a) = 0.36 g

mass of magnesium oxide (c − a) = 0.60 g

mass of oxygen combined with magnesium = 0.60 − 0.36 = 0.24 g

0.60 g of magnesium oxide is produced from heating 0.36 g of magnesium.

The results from Figure C3.17 show that:

- The more magnesium used, the more oxygen combines with it from the air and the more magnesium oxide is produced. The graph is a straight line, showing that the ratio of magnesium to oxygen in magnesium oxide is fixed. A definite compound is formed by a chemical reaction.
- A particular compound always contains the same elements and these elements are always present in the same proportions by mass. It does not matter where the compound is found, or how it is made, these proportions cannot be changed.

In this example, magnesium oxide always contains 60% magnesium and 40% oxygen by mass. Experiments on other compounds show the same pattern. For example, ammonium nitrate always contains 35% nitrogen, 60% oxygen and 5% hydrogen by mass.

Calculating reacting masses from equations

Relative molecular or formula masses can also be used to calculate the amounts of compounds reacted together or produced in reactions (Worked example C3.06).

Calculations of quantities like these are a very important part of chemistry. These calculations show that there is a great deal of information 'stored' in chemical formulae and equations. The equation for the reaction between magnesium and oxygen defines the proportions in which the two elements always react (Figure C3.18).

Magnesium reacts with oxygen to form magnesium oxide. Figure C3.18 shows how to work out the reacting masses and the product mass.

$$2Mg + O_2 \rightarrow 2MgO$$

2 magnesium atoms + 2 oxygen atoms → 2 magnesium atoms + 2 oxygen atoms

Mg = 24 O = 16

$(2 \times 24) + (2 \times 16) = [(2 \times 24) + (2 \times 16)]$

$48 + 32 = [48 + 32]$

$48 + 32 = 80$

For the product, work out the inner brackets first.

48 + 32 → 80

48 grams of magnesium react with 32 grams of oxygen to form 80 grams of magnesium oxide.

Figure C3.18: The proportions in which magnesium and oxygen react are defined by the chemical equation for the reaction.

WORKED EXAMPLE C3.06

Calculating the amounts of compounds reacted together or produced in reactions

If 0.24 g of magnesium react with 0.16 g of oxygen to produce 0.40 g of magnesium oxide (Figure C3.18), how much magnesium oxide (MgO) will be produced by burning 12 g of magnesium?

We have:

0.24 g Mg producing 0.40 g MgO

so 1 g Mg produces $\frac{0.40}{0.24}$ g MgO

= 1.67 g MgO

so 12 g Mg produces 12 × 1.67 g MgO

= 20 g MgO

Using this method based on simple proportions, calculate the mass of calcium oxide formed if 8.0 g of calcium carbonate are decomposed completely by heating. A previous experiment had shown that 20.0 g of calcium carbonate produces 11.2 g of calcium oxide when heated.

20.0 g of calcium carbonate produces 11.2 g of calcium oxide.

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CONTINUED

Therefore, 1 g of calcium carbonate produces $\frac{11.2}{20.0}$ g of calcium oxide.

Therefore, 8.0 g of calcium carbonate produces $\frac{11.2}{20.0} \times 8.0$ g of calcium carbonate = 4.48 g.

Questions

C3.07 Figure C3.19 represents the structures of six different compounds A–F.

- **a** What type of bonding is present in compounds A, C, D, E and F?
- **b** What type of bonding is present in compound B?
- **c** State the molecular formula or formula unit for each compound A–F.

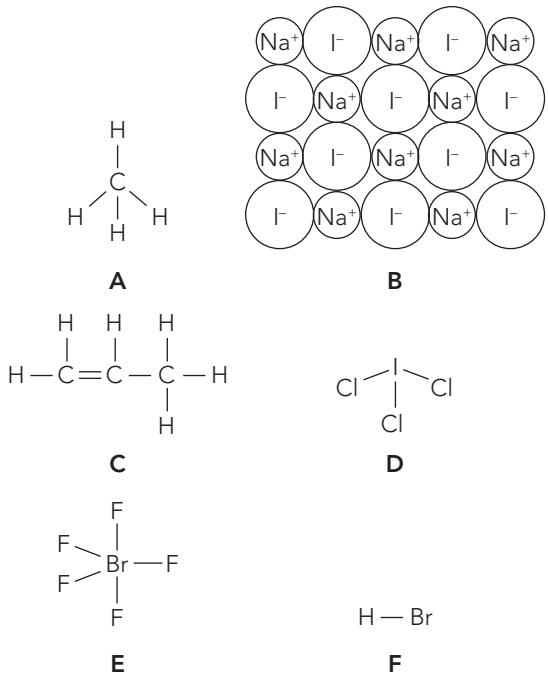

Figure C3.19: Diagrams representing the structures of several different compounds.

C3.08 Calculate the relative molecular or formula masses (M_r) of the following substances:

- **a** oxygen, O_2
- **b** ammonia, NH_3
- **c** sulfuric acid, H_2SO_4
- **d** potassium bromide, KBr
- **e** copper nitrate, $Cu(NO_3)_2$

(A_r: H = 1, N = 14, O = 16, S = 32, K = 39, Cu = 64, Br = 80)

C3.09 Calcium carbonate has the formula $CaCO_3$. What is its relative formula mass (M_r)? (A_r: Ca = 40, C = 12, O = 16)

REFLECTION

Do you have a successful strategy to help you balance equations? What aspects do you find easy or difficult?

Could you explain how to calculate relative molecular or formula masses to someone else?

C3.03 The mole and the Avogadro constant

When a chemist carries out an experiment, they cannot weigh out a single atom or molecule and then react it with another atom or molecule. Atoms and molecules are simply too small. A 'counting unit' must be found that is useful in practical chemistry. This idea is not unusual when dealing with large numbers of small objects. For example, banks weigh coins rather than count them. They know that a fixed number of a particular coin will always have the same mass.

Chemists count atoms and molecules by weighing them. For example, we can measure concentrations (the amount of a substance in a given volume) in g/dm^3.

However, the mass in grams does not immediately tell us the number of particles present because different elements have different masses. Hence, we often use the **mole** as our measure. The mass of one mole of any substance will be equal to the M_r of that substance. This is known as the **molar mass** (see Table C3.06).

KEY WORDS

mole: the measure of amount of substance in chemistry; 1 mole of a substance has a mass equal to its relative formula mass in grams – that amount of substance contains 6.02×10^{23} (the Avogadro constant) atoms, molecules or formula units depending on the substance considered.

molar mass: the mass, in grams, of 1 mole of a substance.

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Substance	Formula	Relative formula mass, M_r	Mass of 1 mole (molar mass)	This mass (1 mole) contains
carbon	C	12	12 g	6.02×10^{23} carbon atoms
iron	Fe	56	56 g	6.02×10^{23} iron atoms
hydrogen	H_2	2 × 1 = 2	2 g	6.02×10^{23} H_2 molecules
oxygen	O_2	2 × 16 = 32	32 g	6.02×10^{23} O_2 molecules
water	H_2O	(2 × 1) + 16 = 18	18 g	6.02×10^{23} H_2O molecules
magnesium oxide	MgO	24 + 16 = 40	40 g	6.02×10^{23} MgO 'formula units'
calcium carbonate	$CaCO_3$	40 + 12 + (3 × 16) = 100	100 g	6.02×10^{23} $CaCO_3$ 'formula units'
silicon(IV) oxide	SiO_2	28 + (2 × 16) = 60	60 g	6.02×10^{23} SiO_2 'formula units'

Table C3.06: Calculating the mass of 1 mole of various substances.

One mole of any substance contains the same number of atoms, molecules or formula units (Table C3.06). The number of particles per mole is named after the 19th-century Italian chemist Amedeo Avogadro and is 6.02×10^{23} particles per mole (this is called the **Avogadro constant** and it is given the symbol L). This means that as we know that 46 g of ethanol is 1 mole of ethanol, we also know that there are 6.02×10^{23} ethanol molecules in this amount of ethanol.

One mole of a substance:

- contains 6.02×10^{23} (the Avogadro constant) atoms, molecules or formula units, depending on the substance considered
- has a mass equal to its relative molecular (or formula) mass (M_r) in grams.

KEY WORDS

Avogadro constant: the number (6.02×10^{23}) of characteristic particles in 1 mole of a substance.

Calculations involving the mole

Mass calculations

You can find the molar mass (mass of one mole) of any substance by following these steps.

1. Write down the formula of the substance; for example, ethanol is C_2H_5OH.
2. Work out its relative formula mass; for example, ethanol contains two carbon atoms ($A_r = 12$), six hydrogen atoms ($A_r = 1$) and one oxygen atom ($A_r = 16$). So for ethanol $M_r = (2 \times 12) + (6 \times 1) + 16 = 46$.
3. Express this in grams per mole; for example, the molar mass of ethanol is 46 g/mol.

For any given mass of a substance:

$$\text{amount (number of moles)} = \frac{\text{mass (in g)}}{\text{molar mass (in g/mol)}}$$

WORKED EXAMPLE C3.07

Using calculation triangles 1

How many moles are there in 60 g of sodium hydroxide?

The relative formula mass of sodium hydroxide is:

M_r (NaOH) = 23 + 16 + 1 = 40

molar mass of NaOH = 40 g/mol

Using a calculation triangle (Figure C3.20) is a useful aid to memory. Cover the quantity to be found and you are left with how to work it out. It is possible to convert any mass of a particular substance into moles, or vice versa.

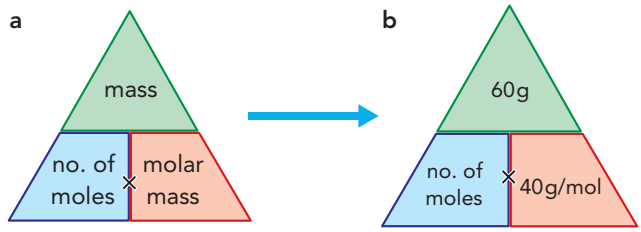

Figure C3.20 a: Calculation triangle. **b:** Using the triangle to work out the number of moles in 60 g of sodium hydroxide.

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CONTINUED

Using the calculation triangle in Figure C3.20b, we see that:

$$\text{number of moles} = \frac{\text{mass}}{\text{molar mass}}$$

$$= \frac{60\text{ g}}{40\text{ g/mol}}$$

$$= 1.5 \text{ moles}$$

By rearranging this triangle we can also carry out calculations to work out amount (number of moles) or the molar mass when given the other values. Remembering that the molar mass is the mass of 1 mole of a substance, we know that this is the same as the relative atomic or formula mass.

Calculating reacting amounts

We can now see that the chemical equation for a reaction is more than simply a record of what is produced. As well as telling us *what* the reactants and products are, it tells us *how much* product we can expect from particular amounts of reactants.

When iron reacts with sulfur, the equation is:

$$\text{Fe} + \text{S} \rightarrow \text{FeS}$$

This indicates that we need equal numbers of atoms of iron and sulfur to react. We know that 1 mol of iron (56 g) and 1 mol of sulfur (32 g) contain the same numbers of atoms. Reacting these amounts should give us 1 mol of iron(II) sulfide (88 g). The equation is showing us that:

Fe	+	S	→	FeS
1 mol		1 mol		1 mol
56 g		32 g		88 g

The mass of the product is equal to the total mass of the reactants. This is the law of conservation of mass, which we met earlier in this chapter. Although the atoms have rearranged themselves, their total mass remains the same. In practice, we may not want to react such large amounts. We could scale down the quantities (that is, use smaller amounts). However, the mass of iron and the mass of sulfur must always be in the ratio 56 : 32.

We could use:

Fe	+	S	→	FeS
5.6 g		3.2 g		8.8 g

If we tried to react 5 g of sulfur with 5.6 g of iron, the excess sulfur would remain unreacted. Only 3.2 g of sulfur could react with 5.6 g of iron. So, 1.8 g of sulfur (5.0 – 3.2 = 1.8 g) would remain unreacted.

We can use the concept of the mole to find reactant or product masses from the equation for a reaction. There are various ways of doing these calculations. The balanced equation itself can be used as a numerical 'bridge' between the two sides of the reaction (Figure C3.21).

Limiting reactants

When we carry out a reaction, we do not always use the amounts of reactant defined by the equation. Sometimes, we deliberately use too much (an *excess*) of one reactant. Typically, the relative amounts of reactants available to react together will dictate the amount of resulting product. One reactant, known as the **limiting reactant**, will determine this quantity. If the other reactants are not completely used in the process, they are said to be *in excess* (Figure C3.22).

KEY WORDS

limiting reactant: the reactant that is not in excess.

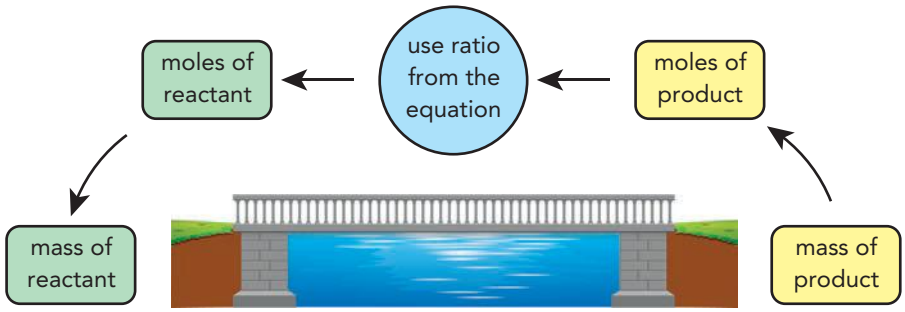

Figure C3.21: A chemical 'bridge'. Following the sequence 'up–across–down' helps to relate the mass of product made to the mass of reactant used. The 'bridge' can also be used in the reverse direction.

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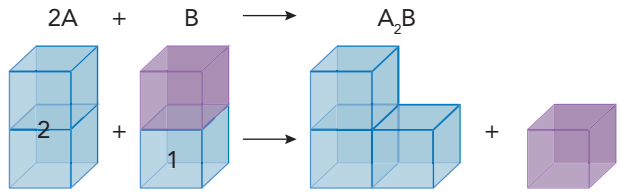

Figure C3.22: Illustrating how excess reactant B (in purple) remains unused after the reaction has taken place.

WORKED EXAMPLE C3.08

Calculating the mass of aluminium oxide produced when aluminium reacts with oxygen

What mass of aluminium oxide is produced when 9.2 g of aluminium metal reacts completely with oxygen gas?

To answer this question, we first work out the balanced equation:

$$4Al + 3O_2 \rightarrow 2Al_2O_3$$

ratio = 4 mol : 2 mol

9.2 g → mass = ?

Then we work through the steps of the 'bridge'.

Step 1 (the 'up' stage): Convert 9.2 g of Al into moles:

$$\text{number of moles} = \frac{9.2\text{ g}}{27\text{ g/mol}}$$

$$= 0.34\text{ mol}$$

Step 2 (the 'across' stage): Use the ratio from the equation to work out how many moles of Al_2O_3 are produced:

4 mol of Al produce 2 mol of Al_2O_3 so

0.34 mol of Al produce 0.17 mol of Al_2O_3

Step 3 (the 'down' stage): Work out the mass of this amount of aluminium oxide (the relative formula mass of Al_2O_3 is 102):

$$0.17\text{ mol} = \frac{\text{mass}}{102\text{ g/mol}}$$

So, the mass of Al_2O_3 produced = 0.17 × 102 g = 17.3 g

Remember to read questions on reacting masses carefully. If you set out the calculation carefully using the equation, as we have done here, you will be able to see which substances are relevant to your calculation. Remember to also take the balancing numbers into account in doing your calculation (this is called the stoichiometry of the equation).

In the reaction between aluminium and oxygen (Worked example C3.08), we needed to make sure that the metal reacted completely with oxygen. We do this by using an excess of oxygen, some of which will not be used up. The amount of aluminium oxide produced is decided by the mass of aluminium we start with, so aluminium is the limiting reactant in this case.

A reaction stops when the limiting reactant is used up. You can find which reactant is limiting by doing the following simple calculation:

- Work out the number of moles of each reactant involved.
- Then divide each by its balancing number (coefficient) in the balanced symbol equation.
- The smallest number indicates the limiting reactant.

WORKED EXAMPLE C3.09

Limiting reactants and reactants in excess

6.0 g of cobalt(II) carbonate was reacted with 0.08 mol of hydrochloric acid to produce cobalt(II) chloride. Show that the cobalt(II) carbonate was in excess.

$CoCO_3(s) + 2HCl(aq) \rightarrow CoCl_2(aq) + H_2O(l) + CO_2(g)$

(A_r: Co = 59; C = 12; O = 16)

M_r of cobalt carbonate = 59 + 12 + (3 × 16) = 119 g/mol

number of moles of cobalt carbonate = 6.0 ÷ 119 = 0.05 mol

From the balanced equation:

- 1 mol cobalt(II) carbonate reacts with 2 mol hydrochloric acid
- 0.05 mol cobalt(II) carbonate would react with 0.10 mol hydrochloric acid
- in this reaction, there was only 0.08 mol of hydrochloric acid, so the cobalt(II) carbonate is in excess.

KEY WORDS

Avogadro's law: equal volumes of any gas, under the same conditions of temperature and pressure, contain the same number of particles.

room temperature and pressure (r.t.p.): the standard values are 25 °C/298 K and 101.3 kPa/1 atmosphere pressure.

molar gas volume: the volume of 1 mole of any gas under specific conditions of temperature and pressure (24 dm^3 at r.t.p.).

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ACTIVITY C3.02

Getting to grips with the mole

The mole can be a tricky concept, but it is essential to success in chemistry as it links the number of particles of a chemical present to the relative mass of that chemical. In simple terms, the mole is just the chemist's way of explaining the amount of substance present.

You are going to prepare a five-minute lesson to explain the concept of the mole to your classmates. To do this, you are going to use the equation for the reaction of lithium with oxygen:

$$4Li + O_2 \rightarrow 2Li_2O$$

Work in a pair to write down an explanation of moles and how they link to mass via M_r. Your explanation should include:

- what the mole is (you might want to include a reference to Avogadro's constant)
- how the balanced equation shows the mole ratios
- how these ratios remain constant, e.g. what would happen if you had 400 moles of Li in terms of the moles of Li_2O produced, or if you only had 0.6 moles of Li
- how an understanding of the number of moles allows masses to be deduced by use of the equation:

$$\text{number of moles} = \frac{\text{mass (g)}}{\text{molar mass}}.$$

You might want to explain why the number of moles in the reactants and products does not have to be the same. In this case, for example, there are five moles of reactants but two moles of products.

Having worked through this example, can you think of another balanced equation and produce a couple of questions to test your classmates' understanding of moles?

Peer assessment

Having constructed a brief lesson on the mole, discuss how successful you thought it was with other members of your group. Use the following questions to help you:

- Were you able to link the ideas suggested in the activity convincingly?
- Did your group think your presentation was clear and understandable?
- What would you change if you were to repeat the activity?
- Could you extend your ideas to include reactions between gases, or in solution?

Mole calculations involving gases

Many reactions, including some of those we have just considered, involve gases. Weighing solids or liquids is relatively straightforward. In contrast, weighing a gas is quite difficult. It is much easier to measure the volume of a gas. But how does gas volume relate to the number of atoms or molecules present?

Equal volumes of *any* gas are found to contain the same number of particles (Table C3.07); this is **Avogadro's law**. This leads to a simple rule about the volume of one mole of a gas.

One mole of any gas occupies a volume of approximately 24 dm^3 (24 litres) at **room temperature and pressure (r.t.p.)**. This is known as the **molar gas volume**.

This rule applies to all gases. This makes it easy to convert the volume of any gas into moles, or moles into volume:

$$\text{number of moles} = \frac{\text{volume (in dm}^3\text{)}}{\text{molar gas volume (= 24 mol/dm}^3\text{ at r.t.p.)}}$$

Remember that 1 dm^3 = 1 litre = 1000 cm^3.

Substance	Molar mass, g/mol	Molar gas volume, dm^3/mol	Number of particles
hydrogen (H_2)	2	24	6.02×10^{23} hydrogen molecules
oxygen (O_2)	32	24	6.02×10^{23} oxygen molecules
carbon dioxide (CO_2)	44	24	6.02×10^{23} carbon dioxide molecules
ethane (C_2H_6)	30	24	6.02×10^{23} ethane molecules

Table C3.07: Molar mass and molar volume of various gases.

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WORKED EXAMPLE C3.10

If 8 g of sulfur are burnt, what volume of SO_2 is produced?

First, consider the reaction of sulfur burning in oxygen.

sulfur	+	oxygen	→	sulfur dioxide
S(s)	+	$O_2(g)$	→	$SO_2(g)$
1 mol		1 mol	→	1 mol
32 g		24 dm^3		24 dm^3

We have:

$$\text{number of moles of sulfur burnt} = \frac{8\,\text{g}}{32\,\text{g/mol}}$$
$$= 0.25\,\text{mol}$$

From the equation:

1 mol of sulfur → 1 mol of SO_2

Therefore:

0.25 mol of sulfur → 0.25 mol of SO_2

So, from the above rule:

$$\text{number of moles} = \frac{\text{volume}}{\text{molar volume}}$$
$$0.25\,\text{mol} = \frac{\text{volume}}{24\,\text{dm}^3/\text{mol}}$$
$$\text{volume of sulfur dioxide} = 0.25 \times 24\,\text{dm}^3$$
$$= 6\,\text{dm}^3 \text{ at r.t.p.}$$

Some important reactions involve only gases. For such reactions, the calculations of expected yield are simplified by the fact that the value for molar volume applies to any gas.

For example:

hydrogen	+	chlorine	→	hydrogen chloride
$H_2(g)$	+	$Cl_2(g)$	→	2HCl(g)
1 mol		1 mol		2 mol
24 dm^3		24 dm^3		48 dm^3

The volumes of the gases involved are in the same ratio as the number of moles given by the equation:

$H_2(g)$	+	$Cl_2(g)$	→	2HCl(g)
1 volume		1 volume		2 volumes

So, if we react 20 cm^3 of hydrogen with sufficient chlorine, it will produce 40 cm^3 of hydrogen chloride gas.

REFLECTION

Think about the following questions:

- Did you face any problems when learning about the concept of the mole in this chapter?
- Are there any maths skills that you feel it would be helpful to improve?

Questions

C3.10 Calculate the number of moles of gas there are in:

- **a** 480 cm^3 of argon
- **b** 48 dm^3 of carbon dioxide
- **c** 1689 cm^3 of oxygen.

C3.11 Calculate the volume (in cm^3) of the following at r.t.p.

- **a** 1.5 moles of nitrogen
- **b** 0.06 moles of ammonia
- **c** 0.5 moles of chlorine

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PROJECT C3.01 THE MOLE AND A GREEN APPROACH TO INDUSTRIAL CHEMISTRY

The concept of the mole and the ratios in which chemicals react are very important in discussing the conditions used in key industrial processes such as the Haber and Contact processes. These ideas have become part of the Green Chemistry approach to industrial processes (Figure C3.23). The ideas of Green Chemistry are proposed in a set of 12 principles (Figure C3.24).

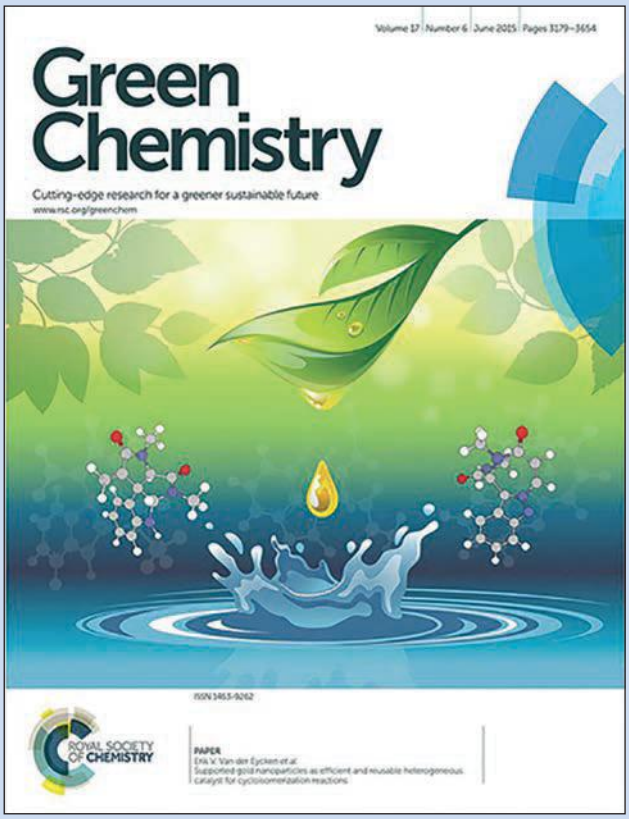

Figure C3.23: The cover of the science journal published by the Royal Society of Chemistry concerned with the development of ideas of Green Chemistry.

These principles cover such ideas as:

- maximising the amount of the raw materials that ends up in the desired product; measured as atom economy
- using renewable raw materials and energy sources
- using the least environmentally harmful substances and solvents
- using energy efficient processes
- avoiding the production of waste.

In groups, research and discuss the principles of Green Chemistry. Focus on these questions in your discussion:

- Why might a green approach to chemistry be important for industrial processes?
- Which of the principles do you think are the most important? Why?
- How do these ideas link to what you have learnt in this chapter?

1. Prevent waste
2. Maximise atom economy
3. Less hazardous chemicals
4. Safer chemicals and products
5. Safer solvents and reaction conditions
6. Increase energy effciency
7. Use renewable feedstocks
8. Reduce derivatives
9. Use catalysts
10. Design degradable products
11. Analyse for pollution control
12. Accident prevention

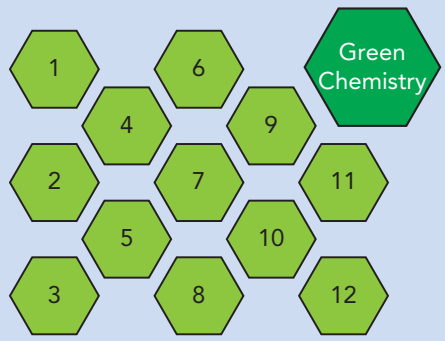

Figure C3.24: The 12 principles of Green Chemistry.

Following your discussion, work in groups to prepare a podcast for the class to listen to explaining the importance of the green approach to industrial chemistry.

In your podcast, include ideas on the following:

- Why is it important to have a balanced symbol equation for your reaction?
- Why is it important to consider limiting reactants and those in excess in an industrial reaction?

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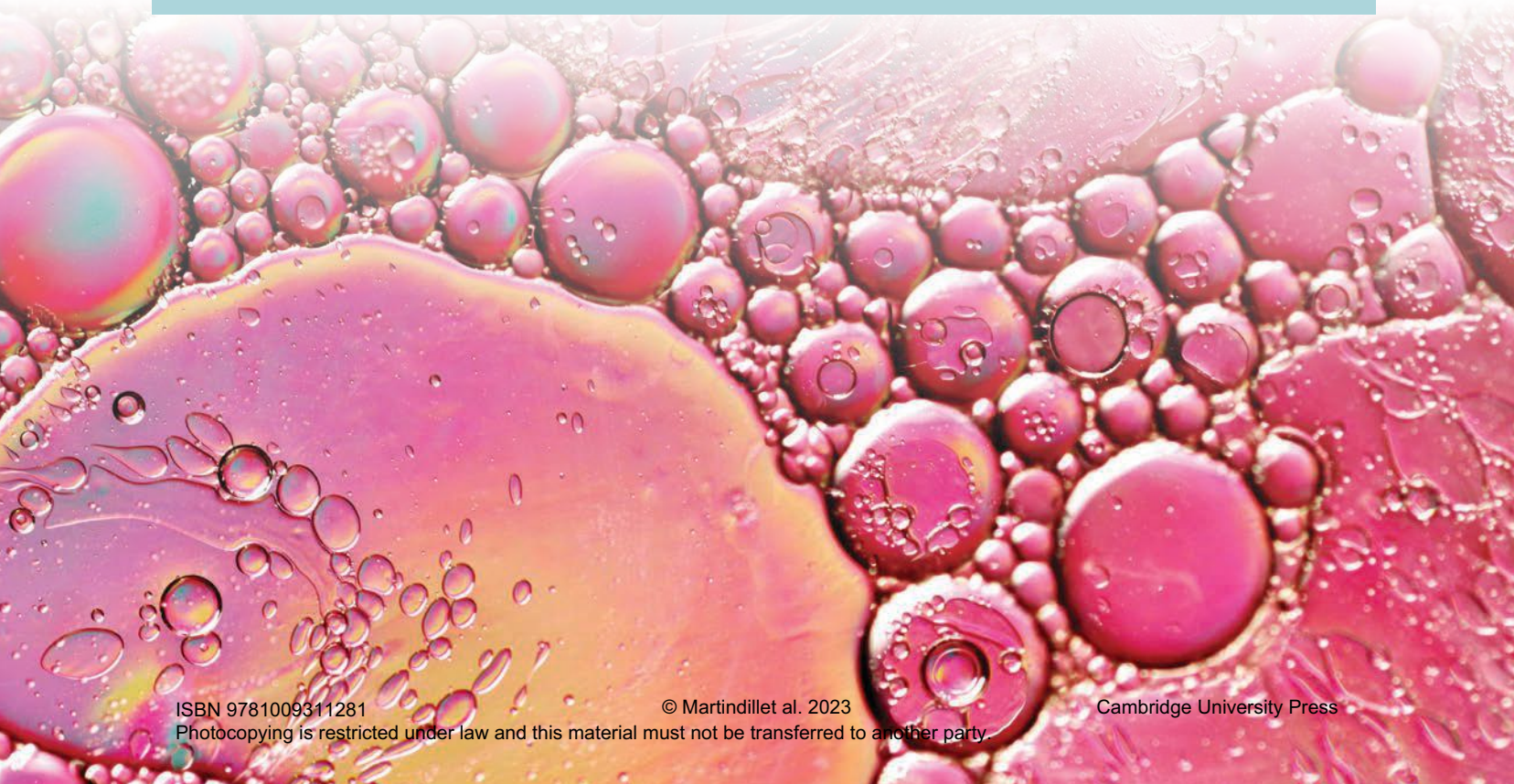
SUMMARY

Elements and compounds can be represented by chemical formulae using the symbols of the elements present and showing the numbers of atoms present in the molecule.
The formula of a simple covalent compound can be deduced from a model or diagram of the structure.
The formula of an ionic compound can be determined from the charges on the ions present or from diagrams representing the structure.
Chemical reactions can be represented by word equations and balanced symbol equations.
State symbols can be used to show the physical states of the reactants and products.
Ionic equations can be constructed for appropriate chemical reactions.
Values for relative atomic mass (A_r) can be used to calculate the relative molecular (formula) mass (M_r) of a compound. This information can then be used to calculate the masses of substances involved in a chemical reaction.
Simple proportions can be used to calculate reacting masses.
Concentration can be measured in g/dm^3.
One mole of a substance contains 6.02×10^{23} particles; this is known as Avogadro's constant.
The molar mass is equal to the relative molecular or formula mass of a substance in grams.
The equation $$\text{amount of substance (mol)} = \frac{\text{mass(g)}}{\text{molar mass(g/mol)}}$$ can be used to calculate mass, number of moles and molar mass.
The balanced chemical equation for a reaction and molar amounts can be used to calculate the reacting masses of substances involved and the amount of product formed.
One mole of any gas has a volume of 24 dm^3 at room temperature and pressure (r.t.p.).



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PRACTICE QUESTIONS

1 Every atom has its own atomic mass, A_r. These are added together to find the relative formula mass, M_r, of a substance. The M_r value for calcium carbonate, $CaCO_3$, is 100.

Identify what mass of carbon is present in 100 g of calcium carbonate.

A 12 g

B 60 g

C 48 g

D 36 g **[1]**

2 Hydrogen peroxide solution is used as a bleach and to clean oil paintings.

A solution of hydrogen peroxide contains 10 g of hydrogen peroxide in every 100 cm^3 of solution. Identify the concentration of the solution in g/dm^3.

A 10 g/dm^3

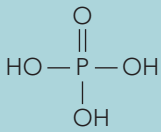
B 20 g/dm^3

C 50 g/dm^3

D 100 g/dm^3 **[1]**

3 Aqueous phosphoric acid reacts with magnesium carbonate to form magnesium phosphate, water and carbon dioxide gas.

a Phosphoric acid has the structure shown in the figure.



State its molecular formula. **[1]**

b **Give** the word equation for the reaction between magnesium carbonate and phosphoric acid, including state symbols. **[2]**

c Solid magnesium carbonate has the formula $MgCO_3$. **Calculate** its relative formula mass. **[2]**

d **Define** *relative formula mass*. **[1]**

e 6 g of magnesium reacts to form 21 g of magnesium carbonate.

Calculate the mass of magnesium carbonate formed from 1.2 g of magnesium. **[2]**

[Total: 8]

COMMAND WORDS

identify: name/select/recognise

COMMAND WORDS

state: express in clear terms.

give: produce an answer from a given source or recall/memory.

calculate: work out from given facts, figures or information.

define: give a precise meaning.

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CONTINUED

4 When propane, C_3H_8, burns completely in air, carbon dioxide and water are formed.

a Give a symbol equation for the reaction. **[2]**

b Calculate the volume of carbon dioxide, measured at r.t.p. that will be formed when 100 cm^3 of propane is burned. **[2]**

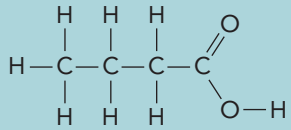
c 50 cm^3 of methane is burned in 150 cm^3 of oxygen:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

Calculate the total volume of the mixture after reaction measured at r.t.p. **[3]**

[Total: 7]

5 The structure of butanoic acid is shown in the figure.



a Give the molecular formula of butanoic acid. **[1]**

b Calculate the molecular mass of butanoic acid. **[1]**

c Butanoic acid dissolves in water forming butanoate and hydrogen ions.

$$C_3H_7COOH \rightarrow C_3H_7COO^- + H^+$$

Magnesium reacts with butanoic acid solution to form a salt, magnesium butanoate and hydrogen. Give a symbol equation for this reaction, including state symbols. **[4]**

d Butanoic acid has a molecular mass. Magnesium butanoate has a formula mass. **Outline** one definition that applies to both these terms. **[2]**

e **Explain** why different terms are used for the two quantities. **[1]**

[Total: 9]

COMMAND WORDS

outline: set out main points.

explain: set out purposes or reasons / make the relationships between things evident / provide why and/or how and support with relevant evidence.

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SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
write the chemical formulae of elements and compounds	C3.01			
deduce the formula of a simple covalent molecule from a model or diagram	C3.01			
write word equations and interpret balanced symbol equations for chemical reactions	C3.01			
deduce the formula of an ionic compound from a model or diagram	C3.01			
write word equations and interpret balanced symbol equations for chemical reactions, including the use of state symbols	C3.01			
understand how to construct symbol and ionic equations for appropriate reactions	C3.01			
use relative atomic masses to calculate the relative molecular (formula) mass for a compound and use this information to calculate the masses involved in reactions	C3.02			
use proportions to calculate reacting masses	C3.02			
know that concentration can be measured in g/dm^3	C3.03			
understand that the mole is a standard number (Avogadro's constant) of characteristic particles (atoms, ions or molecules) of a substance	C3.03			
calculate the relationship between the number of moles of a substance and the mass or number of particles present in a sample of a substance	C3.03			
use the information given in an equation to calculate reacting masses, limiting reagents and amount of product for a stated reaction	C3.03			
understand that the molar gas volume for any gas is $24\,dm^3$ at room temperature and pressure, and be able to use this value for calculations on reactions involving gases.	C3.03			

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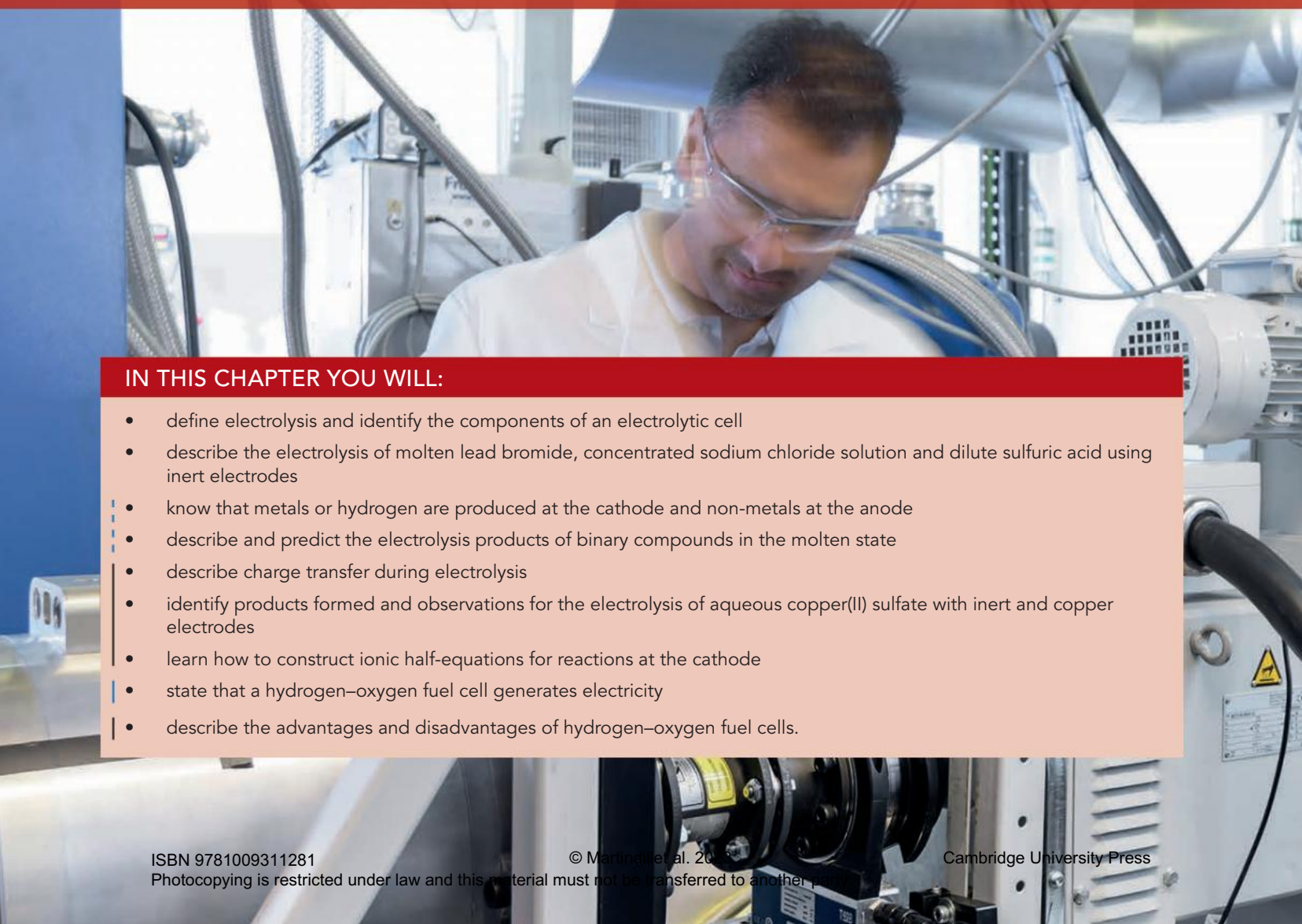
C4 Electrochemistry

All learners study some content in this chapter



IN THIS CHAPTER YOU WILL:

- define electrolysis and identify the components of an electrolytic cell
- describe the electrolysis of molten lead bromide, concentrated sodium chloride solution and dilute sulfuric acid using inert electrodes
- know that metals or hydrogen are produced at the cathode and non-metals at the anode
- describe and predict the electrolysis products of binary compounds in the molten state
- describe charge transfer during electrolysis
- identify products formed and observations for the electrolysis of aqueous copper(II) sulfate with inert and copper electrodes
- learn how to construct ionic half-equations for reactions at the cathode
- state that a hydrogen–oxygen fuel cell generates electricity
- describe the advantages and disadvantages of hydrogen–oxygen fuel cells.

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BEFORE YOU START

Arrange yourselves into groups within the class and discuss your background understanding of **electrical conductivity**. Discuss the following questions:

1 From your everyday experience, which metals have you seen most often used in electrical wiring, both domestically and in computer circuit boards?

2 Why is wiring usually covered with a plastic coating?

3 Do liquid metals conduct electricity? What other kinds of liquid are able to conduct electricity?

Summarise the answers from your group and report back to the whole class.

KEY WORDS

electrical conductivity: the ability to conduct electricity.

SCIENCE IN CONTEXT C4.01

Electrochemistry and the economy

There are many industrially and economically important uses of electrochemistry. For example:

1 Electrolysis is used to purify aluminium from bauxite, its major ore which takes its name from the medieval village of Les Baux where it was first mined. In this process, bauxite is first treated with sodium hydroxide to produce aluminium oxide. The aluminium oxide is then dissolved in molten cryolite. Cryolite is used to reduce the temperature that is needed for the process, thus decreasing the energy demand of this process.

2 Electroplating is used to coat one metal onto another (Figure C4.01). This has a wide range of applications. One of the most important is adding a protective coating to the base metal to prevent corrosion. In this process, electricity is used to deposit the coating onto the base metal.

3 The chemical reaction between hydrogen and oxygen is a simple reaction which produces water. This reaction gives out a large amount of energy. The hydrogen–oxygen fuel cell uses an electrochemical process to convert the chemical energy of the reaction into electricity and seems to be one of the better options to reduce the dependence of our transport systems on fossil fuels.

Discussion questions

1 For the processes above, the substances involved need to be either a liquid or molten. Use your knowledge of ionic bonding to explain why this is the case.

2 There are many other processes which involve electricity. One of these involves brine, or aqueous sodium chloride. Thinking about the ions present here, suggest what the products of decomposition, or breakdown, of aqueous sodium chloride could be and why these might be important.

3 For each of the processes outlined above, suggest why these might be economically important, considering the products of each process.

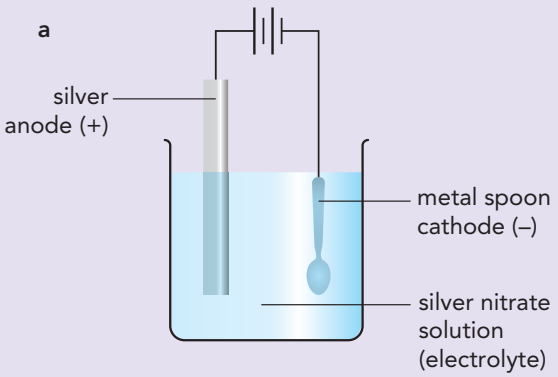

Figure C4.01 a: Cell for electroplating with silver. **b:** Industrial electroplating of metal objects.

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C4.01 Electrolysis

Conductivity

All metals conduct electricity, but carbon in the form of graphite is the only non-metallic element that conducts electricity. Metals and graphite conduct electricity because they have mobile free electrons (e^-) in their structure.

A simple circuit can be used to test if a solid conducts electricity (Figure C4.02). The circuit is made up of a battery (a source of direct current), some connecting copper wires fitted with clips, and a light bulb to show when a current is flowing. The material to be tested is clipped into the circuit. The battery 'pumps' free electrons in one direction around the circuit. If the bulb lights up, then the material is an **electrical conductor**.

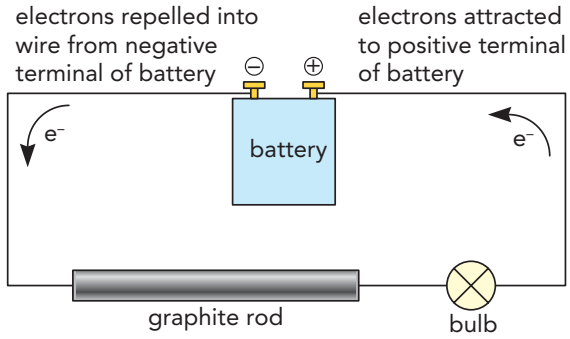

Figure C4.02: Testing a solid material (a graphite rod) to see if the material conducts electricity; the bulb will light if the material is an electrical conductor.

There is no chemical change when an electric current is passed through a metal or graphite. A copper wire is still copper when the current is switched off.

Solid covalent non-metals do not conduct electricity because there are no free electrons – they are all involved in bonding. Such substances are called non-conductors or **electrical insulators** (Table C4.01).

Electrolytes	Non-electrolytes
sulfuric acid	distilled water
molten lead bromide	ethanol
sodium chloride solution	petrol
copper(II) chloride solution	molten sulfur
sodium hydroxide solution	sugar solution

Table C4.01: Some electrolytes and non-electrolytes.

Some liquids conduct electricity. The process in which an electric current flows through a liquid compound or solution is called **electrolysis**. Unlike electrical conductivity in metals, electrolysis in liquid compounds or solutions produces a chemical reaction, causing the substance to change.

The conductivity of liquids can be tested in a similar way to solids, but the simple testing circuit is changed (Figure C4.03). Instead of clipping the solid material to be tested into the circuit, graphite rods are dipped into the test liquid. Liquid compounds, solutions and molten materials can all be tested in this way.

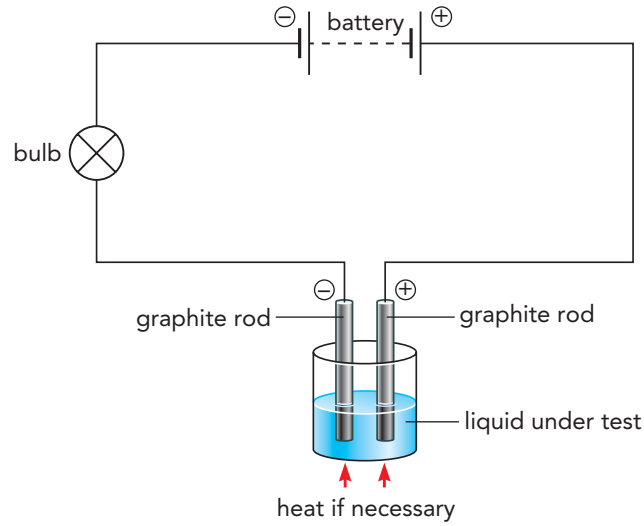

Figure C4.03: Apparatus for testing the conductivity of liquids (an electrolytic cell).

If liquid compounds or solutions are tested using the apparatus in Figure C4.03, then the result will depend on the type of bonding in the compound (Chapter C2). Molten metals, and mercury, which is liquid at room temperature, conduct electricity. Electrons are still able to move through the liquid metal to carry the charge. As in solid metals, no chemical change takes place when liquid metals conduct electricity. If the compound is bonded covalently, then the compound will *not* conduct electricity as a liquid or as a solution.

KEY WORDS

electrical conductor: a substance that conducts electricity but is not chemically changed in the process.

electrical insulator: a substance that does not conduct electricity.

electrolysis: the breakdown of an ionic compound, molten or in aqueous solution, by the use of electricity.

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Examples of such liquids are ethanol, petrol (gasoline), pure water and sugar solution. Ionic compounds *will* conduct electricity if they are either molten or dissolved in water. Examples of these ionic compounds are molten lead bromide, sodium chloride solution and copper(II) sulfate solution.

Electrolysis and the movement of ions

When ionically bonded liquids conduct electricity, they do so in a different way from metals. Ionically bonded liquids conduct electricity because the ions (charged particles) present can move through the liquid, carrying the charge. Ionic compounds will not conduct electricity when they are solid because their ions are fixed in position and cannot move (remember that in Chapter C1 we discussed the fact that in solids the particles present can only vibrate about a fixed position). Liquids that conduct electricity through the movement of ions are called **electrolytes** and liquids that do not conduct in this way are called **non-electrolytes** (Table C4.01).

When electrolytes conduct electricity during electrolysis, a chemical change takes place and the ionic compound is broken down (it is decomposed). For example, lead(II) bromide is changed to lead and bromine:

$$\text{lead(II) bromide} \rightarrow \text{lead} + \text{bromine}$$

$$PbBr_2(l) \rightarrow Pb(l) + Br_2(g)$$

Electrolytic cells

The apparatus in which electrolysis is carried out is known as an **electrolytic cell** (Figure C4.03). The direct current is supplied by a battery or power pack. **Inert electrodes** carry the current into and out of the electrolyte. Graphite is often chosen as the inert electrode because it is quite unreactive, so it will not react with the electrolyte or with the products of electrolysis. Platinum electrodes are used in some cells instead of graphite. In the external circuit, electrons flow from the negative terminal of the battery to the **cathode**, and then from the **anode** back to the positive terminal. In the electrolyte it is the ions that move to carry the current.

During electrolysis:

- positive ions (metal ions or H^+ ions) move towards the negative electrode, the cathode; they are known as **cations**
- negative ions (non-metal ions) move towards the positive electrode, the anode; they are known as **anions**.

In an electrolytic cell, charge is transferred in a number of different ways which all happen simultaneously.

- In the external circuit, charge is transferred via the flow of electrons. Electrons move away from the negative terminal and towards the positive.
- At the cathode, electrons move from the electrode to the cations, forming the uncharged species.
- At the anode, electrons move from the anion to the electrode, again, forming the uncharged species.
- In the electrolyte, charge is transferred not by electrons, but rather by the movement of the ions present. Positive ions move towards the negative cathode while negative ions move towards the positive anode.

Together, these steps allow current to flow in a complete circuit. This is shown in the next topic, using lead bromide as an example.

Comparison between conductivity in solids and in electrolytes

The two distinct types of electrical conductivity are called metallic and electrolytic conductivity. They differ from each other in important ways which are outlined in Table C4.02.

KEY WORDS

electrolyte: an ionic compound that will conduct electricity when it is molten or dissolved in water; electrolytes will not conduct electricity when solid.

non-electrolyte: liquid or solution that does not take part in electrolysis; it does not contain ions.

electrolytic cell: a cell consisting of an electrolyte and two electrodes (anode and cathode) connected to an external DC power source where positive and negative ions in the electrolyte are separated and discharged.

electrodes: the points where the electric current enters or leaves a battery or electrolytic cell.

inert electrode: an electrode that is made from a material that will not interact with the electrolyte or the products of electrolysis.

KEY WORDS

cathode: the electrode in any type of cell at which reduction (the gain of electrons) takes place; in electrolysis it is the negative electrode.

anode: the electrode in any type of cell at which oxidation (the loss of electrons) takes place; in electrolysis it is the positive electrode.

cation: a positive ion that would be attracted to the cathode in electrolysis.

anion: a negative ion that would be attracted to the anode in electrolysis.

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Metallic conductivity	Electrolytic conductivity
• electrons flow • a property of elements (metals, and carbon as graphite) and alloys • takes place in solids and liquids • no chemical change takes place	• ions flow • a property of ionic compounds • takes place in liquids and solutions (not solids) • chemical **decomposition** takes place

Table C4.02: Comparison between metallic and electrolytic conductivity.

KEY WORD

decomposition: a type of chemical reaction where a compound breaks down into simpler substances.

ACTIVITY C4.01

Key words in electrical conductivity and electrolysis

The topics of electrical conductivity and electrolysis include a number of key words that cover the nature of different substances and the features of an electrolytic cell. Work in pairs to create a list of the key words for this topic. You can include the key words identified in this chapter to help you.

Once you have completed your list, follow these steps:

1. Label yourselves Partner A and Partner B.
2. Partner A chooses a key word and describes it to Partner B. In your description, you are not allowed to include the key word.
3. Partner B then tries to guess the word that Partner A is explaining.
4. Swap over and take it in turns until you have discussed all of your key words.

After you have finished, create a word cloud of the terms you think are the most important to learn for this topic. Use different sizes and colours to indicate the most straightforward and most difficult terms.

Questions

C4.01 **a** Which of the following will conduct electricity?

- **i** a strip of copper metal
- **ii** a solution of sugar in water
- **iii** aqueous sodium chloride solution
- **iv** mercury
- **v** dilute hydrochloric acid
- **vi** melted sugar

b Which of i–vi are electrolytes?

C4.02 **a** Why is solid potassium bromide a non-conductor of electricity?

b Suggest *two* things that could be done to potassium bromide that would make it conduct electricity.

C4.03 Explain the major difference between electrical conductivity in metals and solutions in terms of the particles that are carrying the current.

Products of electrolysis

Electrolysis of molten ionic compounds

An electrolytic cell can be used to electrolyse molten compounds. Heat must be supplied to keep the salt molten. Figure C4.04 shows the electrolysis of molten lead(II) bromide.

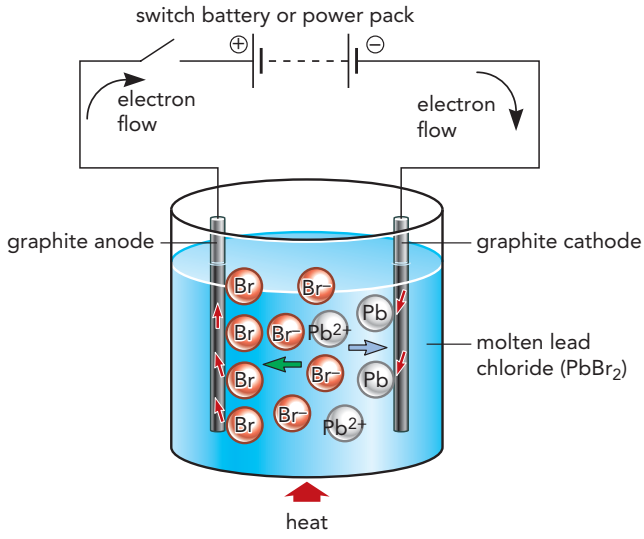

Figure C4.04: Movement of ions in the electrolysis of a molten salt, lead(II) bromide.

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When the switch is closed and the circuit is complete, the current flows. Bromine vapour (which is red–brown) begins to bubble off at the anode and liquid lead forms at the cathode. The electrical energy from the cell has caused a chemical change (decomposition). The cell breaks down (decomposes) the molten lead(II) bromide because the Pb^{2+} and Br^- ions present move to opposite electrodes where they gain and lose electrons, respectively. Figure C4.04 shows this movement.

This movement of the ions means that when a molten ionic compound is electrolysed:

- the metal is always formed at the cathode (the negative electrode)
- the non-metal is always formed at the anode (the positive electrode).

Knowing how a **binary substance** breaks down when electrolysed, we can easily predict the products for a molten, binary ionic compound. Table C4.03 shows some further examples of this type of electrolysis. The electrolysis of molten salts is easier if the melting point of the salt is not too high. The electrolysis of molten ionic salts is important for the industrial extraction of reactive metals such as sodium and magnesium. The extraction of aluminium by the electrolysis of molten aluminium oxide is a very important process and is covered later in this chapter.

Electrolyte (compound electrolysed)	Product at cathode (negative electrode)	Product at anode (positive electrode)
lead bromide, $PbBr_2$	lead (Pb)	bromine (Br_2)
sodium chloride, NaCl	sodium (Na)	chlorine (Cl_2)
potassium iodide, KI	potassium (K)	iodine (I_2)
copper(II) bromide, $CuBr_2$	copper (Cu)	bromine (Br_2)
zinc chloride, $ZnCl_2$	zinc (Zn)	chlorine (Cl_2)
aluminium oxide (Al_2O_3)	aluminium (Al)	oxygen (O_2)

Table C4.03: Some examples of the electrolysis of molten salts.

The movement of ions to the different electrodes during electrolysis results in the breakdown of the ionic compound. Different reactions take place at the two electrodes. Look at the electrolysis of molten lead(II) bromide in more detail (Figure C4.05).

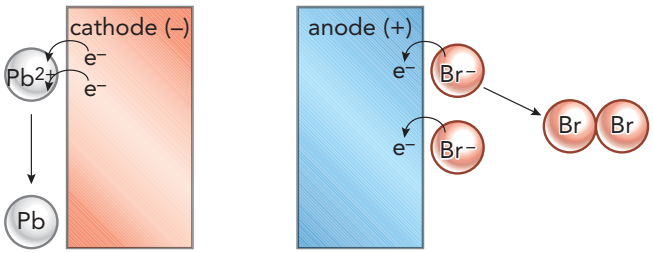

Figure C4.05: At the cathode, metal ions gain electrons. At the anode, non-metal ions lose electrons.

During electrolysis, the bromide ions (Br^-) move to the anode. Each bromide ion gives up (donates) one electron to become a bromine atom:

$$\text{At the anode: } Br^- \rightarrow Br + e^-$$

Two of these bromine atoms bond together to make a bromine molecule:

$$Br + Br \rightarrow Br_2$$

The lead ions (Pb^{2+}) move to the cathode. There, each lead ion gains (accepts) two electrons and becomes a lead atom:

$$\text{At the cathode: } Pb^{2+} + 2e^- \rightarrow Pb$$

During electrolysis, the flow of electrons continues through the circuit. For every two electrons taken from the cathode by a lead ion, two electrons are set free at the anode by two bromide ions. So, overall, the electrons released at the anode flow through the circuit towards the cathode. During the electrolysis of molten salts, the metal ions, which are always positive (cations), move to the cathode and are discharged. Non-metal ions (except hydrogen), however, are always negative (anions) and move to the anode to be discharged. Table C4.04 shows the cathode and anode reactions for some examples of electrolysis of molten binary compounds. These electrode reactions are represented by **half-equations**. If the two half-equations are added together, they give the overall equation for the reaction taking place in the electrolytic cell.

KEY WORDS

binary substance: a substance composed from two different elements.

half-equations: ionic equations showing the separate oxidation and reduction steps in redox reactions, including the reactions at the anode (oxidation) and cathode (reduction) in an electrolytic cell.

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Electrolyte	Cathode reaction	Anode reaction
lead bromide, $PbBr_2$	$Pb^{2+} + 2e^- \rightarrow Pb$	$2Br^- \rightarrow Br_2 + 2e^-$
sodium chloride, NaCl	$Na^+ + e^- \rightarrow Na$	$2Cl^- \rightarrow Cl_2 + 2e^-$
aluminium oxide (Al_2O_3)	$Al^{3+} + 3e^- \rightarrow Al$	$2O^{2-} \rightarrow O_2 + 4e^-$
copper(II) bromide, $CuBr_2$	$Cu^{2+} + 2e^- \rightarrow Cu$	$2Br^- \rightarrow Br_2 + 2e^-$

Table C4.04: Electrode half-equations for some examples of the electrolysis of molten salts. Note: you only need to be able to construct equations for the reaction at the cathode.

Electrolysis of solutions

Many ionic compounds dissolve in water. In such solutions, the ions are free to move and therefore these solutions will conduct electricity. The electrolysis of ionic solutions also produces chemical change. However, the products from electrolysis of a solution of a salt may be different from those obtained by electrolysis of the molten salt. This is because water itself dissociates to produce ions.

Although water is a simple molecular substance, a very small fraction of its molecules split into hydrogen ions (H^+) and hydroxide ions (OH^-):

$$H_2O \rightarrow H^+ + OH^-$$

Because only a small number of the water molecules present split into ions, not enough ions are produced to make pure water a good conductor of electricity. Thus, water is a weak electrolyte. During electrolysis, however, these hydrogen and hydroxide ions are also able to move to the electrodes and compete with the ions from the acid or salt to be discharged at the electrodes.

Electrolysis of dilute sulfuric acid

Although water is a very poor conductor of electricity, it can be electrolysed if it is acidified with a few drops of sulfuric acid. An electrolytic cell, such as the one shown in Figure C4.06, sometimes called a Hofmann voltameter, can be used for the electrolysis of the dilute sulfuric acid. This equipment keeps the gases produced separate. The gas produced at the anode is collected on one side and that produced at the cathode is collected on the other.

After the electrolysis has been running for a short time, the volume of gas in each arm of the apparatus can be measured and tested. The gas collected above the cathode is hydrogen. Oxygen collects above the anode. The ratio of the volumes is approximately 2 : 1.

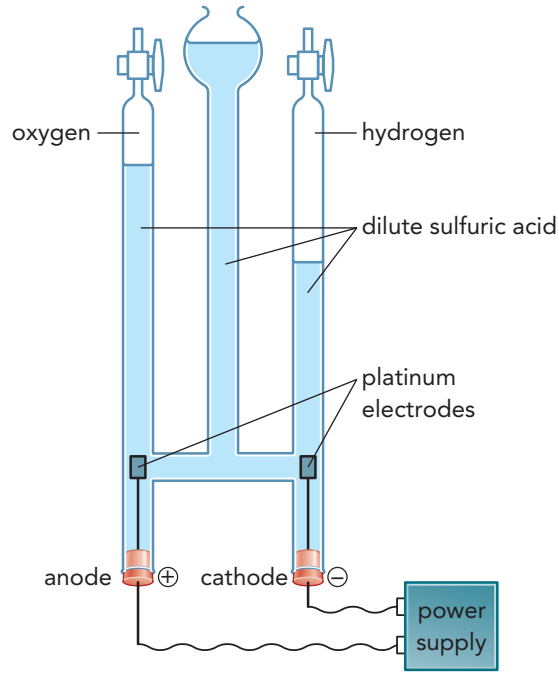

Figure C4.06: A Hofmann voltameter for the electrolysis of dilute sulfuric acid.

The ions present in the solution are H^+, OH^- and SO_4^{2-}. But at each electrode just *one* type of ion gets discharged. Only hydrogen ions move to the cathode, so it is clear why hydrogen gas is produced there. However, both OH^- and SO_4^{2-} move to the anode, but only the hydroxide ions are discharged to give oxygen gas. This is due to the difference in stability of the ions, but you do not need to be able to explain this at this stage. Effectively, this experiment is the electrolysis of water.

$$2H_2O(l) \rightarrow \underset{\text{at the cathode}}{2H_2(g)} + \underset{\text{at the anode}}{O_2(g)}$$

Electrolysis of sodium chloride solution

A concentrated solution of sodium chloride can be electrolysed in the laboratory (Figure C4.07). There are four different ions present in the solution. The positive ions (cations), Na^+ and H^+, flow to the cathode, attracted by its negative charge. The negative ions (anions), Cl^- and OH^-, travel to the anode.

When this experiment is carried out, hydrogen is produced at the cathode, not sodium. Chlorine, a green gas, is collected at the anode. This chlorine is produced by the discharge of chloride ions at the anode. In this case, the hydroxide ions are not discharged and so no oxygen gas is produced.

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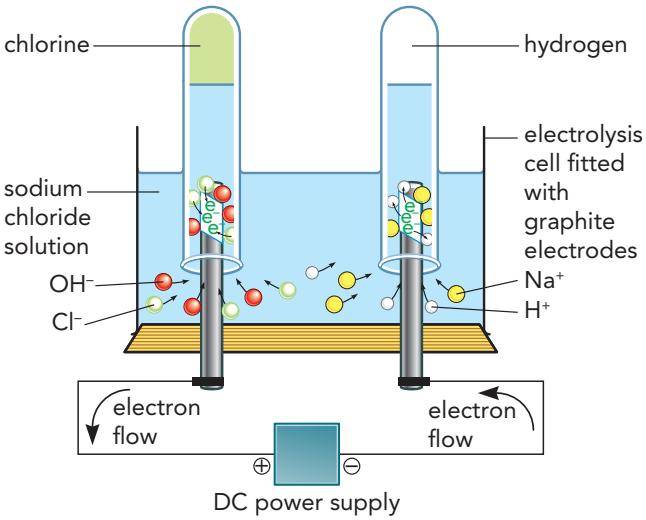

Figure C4.07: Movement and discharge of ions in the electrolysis of concentrated sodium chloride solution.

It is important to understand that different products are formed when concentrated sodium chloride solution is electrolysed rather than molten sodium chloride (Table C4.05).

Electrolyte	Product at cathode	Product at anode
molten sodium chloride, NaCl(l)	sodium (Na)	chlorine (Cl_2)
concentrated sodium chloride solution, NaCl(aq)	hydrogen (H_2)	chlorine (Cl_2)

Table C4.05: Products of electrolysis of sodium chloride under different conditions.

Electrolysis of copper(II) sulfate

Further information on the nature of electrode reactions can be found from experiments using different salt solutions. The electrolysis of a blue copper(II) sulfate solution using inert graphite electrodes (Figure C4.08) produces a deposit of red–brown copper metal on the cathode. Copper is less reactive than hydrogen and therefore it is the copper ions (Cu^{2+}) that are discharged at the cathode.

$$\text{At the cathode: } Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$$

Oxygen gas is produced at the anode as the hydroxide ions from water are discharged rather than the sulfate ions.

$$\text{At the anode: } 4OH^- \rightarrow 2H_2O + O_2 + 4e^-$$

As the electrolysis proceeds, the blue colour of the solution will fade as the copper ions causing the colour are discharged. The electrolyte solution will also become more acidic as OH^- ions are discharged.

Figure C4.08: Copper is quite unreactive so it can be seen deposited on the cathode when copper(II) sulfate solution is electrolysed.

In comparison to this reaction, it is possible to use electrodes other than graphite or platinum; electrodes that are not inert. A cell can be set up to electrolyse copper(II) sulfate solution using copper electrodes (not graphite electrodes). As electrolysis takes place, the cathode gains mass as copper is deposited on the electrode (Figure C4.09).

$$\text{At the cathode: } Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$$

The anode, however, loses mass as copper dissolves from the electrode:

$$\text{At the anode: } Cu(s) \rightarrow Cu^{2+}(aq) + 2e^-$$

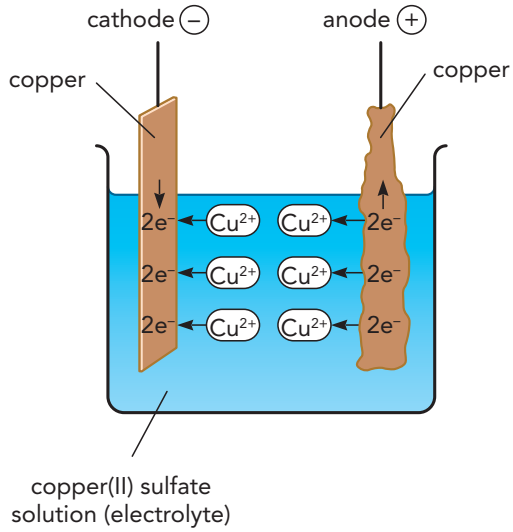

Figure C4.09: The electrolysis of copper(II) sulfate using copper electrodes. The movement of ions effectively transfers copper from one electrode to the other.

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So, overall, there is a transfer of copper from the anode to the cathode. The colour of the copper(II) sulfate solution does not change because the concentration of the Cu^{2+} ions in the solution remains the same. The idea of dissolving anodes is useful in the process of **electroplating** and in the purification of copper.

KEY WORD

electroplating: a process of electrolysis in which a metal object is coated (plated) with a layer of another metal.

REFLECTION

An understanding of electrolysis involves considering several different physical situations: molten electrolytes, solutions of dilute acids or salt solutions. How have you organised the information that deals with these different situations? Do you have a clear strategy for describing the different products formed in these varied examples? How would you explain the key features of electrolysis to someone else?

EXPERIMENTAL SKILLS C4.01

Electrolysis of copper(II) sulfate solution

This experiment is designed to demonstrate the different products obtained when the electrolysis of copper(II) sulfate solution is carried out first with inert graphite electrodes and then with copper electrodes. The use of copper electrodes illustrates how copper is refined industrially.

You will need:

- copper(II) sulfate solution (0.5 mol/dm^3)
- 200 cm^3 beaker
- graphite rods
- stand and clamp(s) for electrodes
- DC power supply
- small light bulb
- connecting leads and crocodile clips
- copper strips (cleaned with sandpaper).

Safety

Wear eye protection throughout. Be careful with chemicals. Never ingest them and always wash your hands after handling them.

CONTINUED: C4.01

Getting started

Consider what you have learnt about electrolytic cells and the process of electrolysis.

- Predict at which electrode you would expect a metal to be deposited.
- Predict at which electrode you would expect a non-metallic gas to be given off.

Finally, check that you can assemble the equipment for the cell for a test run.

Method

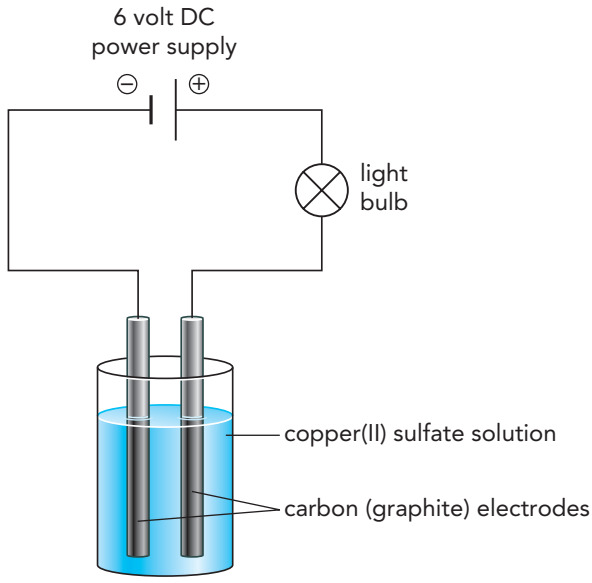

Figure C4.10: Electrolysis of copper(II) sulfate solution with graphite electrodes.

1 Set up the electrolytic cell as shown in Figure C4.10 using graphite rods as electrodes. Observe what happens.

A deposit of copper forms on the cathode; this will often be powdery and uneven. Bubbles of gas (oxygen) are formed at the anode.

At the cathode: $Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$

At the anode: $4OH^-(aq) \rightarrow 2H_2O(l) + O_2(g) + 4e^-$

2 Repeat the experiment, replacing the graphite rods with clean copper strips as electrodes. Observe what happens.

This produces a different anode reaction. No oxygen is produced, rather the copper anode dissolves. Copper can be seen disappearing from the surface of the copper-coated anode:

At the anode: $Cu(s) \rightarrow Cu^{2+}(aq) + 2e^-$

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CONTINUED: C4.01

The reaction is the reverse of the cathode reaction.

During this electrolysis, the mass gained at the cathode is equal to the mass lost at the anode.

Questions

1 Were there ways in which the apparatus you had could be improved?

2 Comment on the steps you would need to take to make the electrolysis with copper electrodes **quantitative**.

Self assessment

Setting up the apparatus for a functioning electrolytic cell requires organisation and practical skill. Would you be able to agree with the following statements as to how you carried out the experiment?

- I was confident when setting up the apparatus for this experiment and I set up everything correctly.
- My electrolytic cell worked and I could see the formation of copper on the cathode.
- I had time to repeat the experiment with copper electrodes.

If not, how could you improve your experiment next time?

KEY WORD

quantitative: the ability to put numerical values to the properties being studied.

Questions

C4.04 What products will you get when you pass an electric current through:

a a concentrated solution of sodium chloride?

b molten potassium chloride?

C4.05 Give a general rule for predicting the electrode products when a molten binary ionic compound is electrolysed.

C4.06 In the electrolysis of molten lead(II) bromide, the reaction occurring at the negative electrode was:

$$Pb^{2+} + 2e^- \rightarrow Pb$$

a Write the equation for the reaction taking place at the positive electrode.

b What observations would be made during this reaction?

C4.02 Hydrogen–oxygen fuel cells

In electrolysis, we put in electrical energy to make a chemical reaction happen. The reaction that takes place is always a decomposition reaction. The change is endothermic; electrical energy is put in to bring about the change. (Endothermic and exothermic processes were introduced in Chapter C1, and will be discussed further in Chapter C5.)

It is possible to reverse this process and use chemical reactions to produce electrical energy. This is what takes place in the electrochemical cells and batteries that we use so often in everyday situations (Figure C4.11). Simple electrochemical cells lose their power and need to be recharged from time to time. Many of the substances found in electrochemical cells are harmful and difficult to dispose of.

Figure C4.11: A collection of some different types and sizes of battery.

A much more efficient way of changing chemical energy into electrical energy is by using a **fuel cell**. Such a cell operates continuously, with no need for recharging. The cell supplies energy as long as the reactants are fed into the electrodes. A hydrogen–oxygen fuel cell (Figure C4.12) uses the reaction between hydrogen and oxygen:

$$2H_2(g) + O_2(g) \rightarrow 2H_2O(l)$$

KEY WORDS

fuel cell: a device for continuously converting chemical energy into electrical energy using a combustion reaction; a hydrogen–oxygen fuel cell uses the reaction between hydrogen and oxygen.

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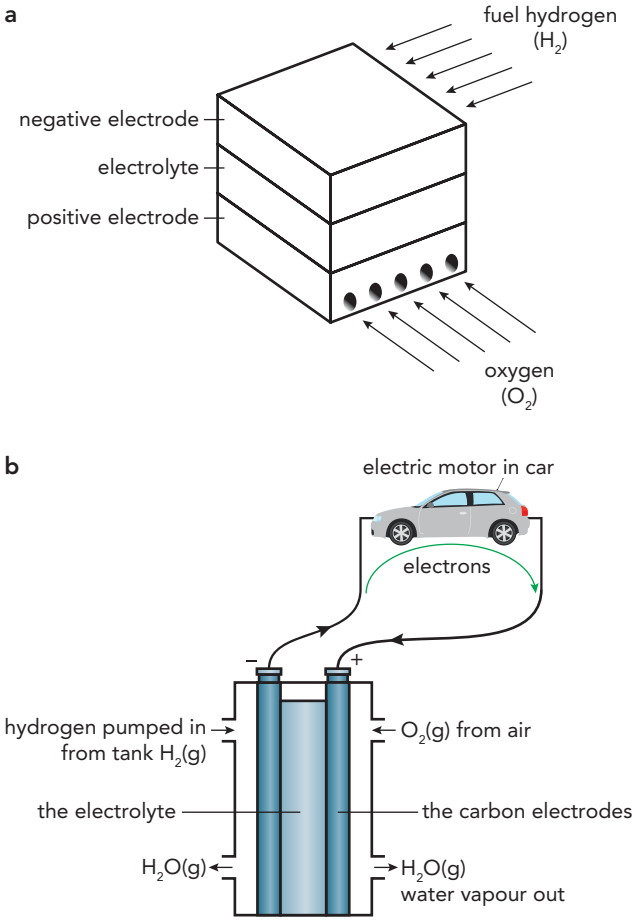

Figure C4.12: Sketches of a hydrogen–oxygen fuel cell. **a:** Hydrogen entering the cell at the negative electrode and oxygen at the positive electrode. **b:** Electrons flowing to a car.

This reaction releases a large amount of energy. Water is the only product. Hydrogen can be regarded as a non-polluting **fuel**.

KEY WORD

fuel: a substance that can be used as a source of energy, usually by burning (combustion).

Hydrogen-powered vehicles

Hydrogen gas has attractions as a fuel. When hydrogen burns, all it produces is water. Also, it produces more energy per gram than any other fuel (Figure C4.13).

Despite difficulties of production, safe storage and transport, several manufacturers have developed prototype hydrogen-powered cars. Some prototypes burn the hydrogen in a modified combustion engine. However, the majority use the hydrogen in a fuel cell. Electricity from this cell then powers an electric motor (Figure C4.14). Using a fuel cell operating an electric motor, hydrogen has an efficiency of 60% compared with 35% for a petrol engine. The advantages and disadvantages are summarised in Table C4.06.

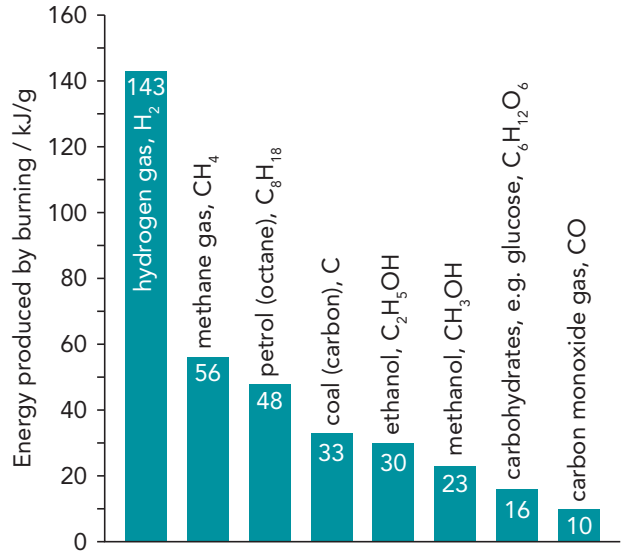

Figure C4.13: Energy produced by burning various fuels. Hydrogen produces more energy per gram than any other fuel.

Figure C4.14: A car powered by hydrogen–oxygen fuel cells.

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A hydrogen–oxygen fuel cell can be used to power a car and in recent years several motor manufacturers worldwide have developed prototypes.

Advantages	Disadvantages
• renewable if produced using solar or wind energy • lower flammability than petrol • virtually emission free • zero emissions of CO_2 • non-toxic	• non-renewable if generated using nuclear energy or energy from fossil fuels • large fuel tank required • as yet there are very few 'filling stations', where a car could be topped up with hydrogen • engine redesign needed or a fuel cell system • currently expensive

Table C4.06: Advantages and disadvantages of hydrogen as a fuel for motor vehicles.

A move to use hydrogen-powered vehicles more extensively would require a greater distribution of hydrogen filling stations. Indeed, fuel cells may be more suited for heavier vehicles and longer distances, suggesting they may be more use for public service vehicles and freight transport vehicles.

Questions

C4.07 In one type of hydrogen–oxygen fuel cell the electrode reactions are:

$$\_\_\_\ H_2(g) \rightarrow \_\_\_H^+(aq) + \_\_\_\ e^-$$

$$O_2(g) + 4H^+(aq) + 4e^- \rightarrow 2H_2O(l)$$

Balance the first of these half-equations so that together they add up to the overall equation:

$$2H_2(g) + O_2(g) \rightarrow 2H_2O(l)$$

C4.08 Sort statements **a–f** into two columns of advantages, one about fuel cells and one about petrol cars:

a virtually emission free
b smaller fuel tank needed
c plentiful filling stations
d non-toxic
e can be renewable
f less expensive

PROJECT C4.01 GENERATING 'GREEN' HYDROGEN FOR MODERN TRANSPORT SYSTEMS

You work for a scientific consultancy and have been asked to explain the process of electrolysis to members of the government to help inform their decisions to establish hydrogen-generating plants in several regions of your country.
Work in groups to prepare a presentation on the process of electrolysis and its environmental impacts. In your presentation, include the following:

- An explanation of the process of electrolysing water to produce hydrogen. Use the structure provided by the explanatory triangle shown in Figure C4.15. This helps to explain the meaning of the word electrolysis and the process involved. Use the example of the electrolysis of dilute sulfuric acid in your explanation.
- Identify the sources of clean energy needed to carry out the electrolysis.
- Suggest how the hydrogen is used to power different types of transport system, and their environmental advantage.

Share your presentations with the whole class.

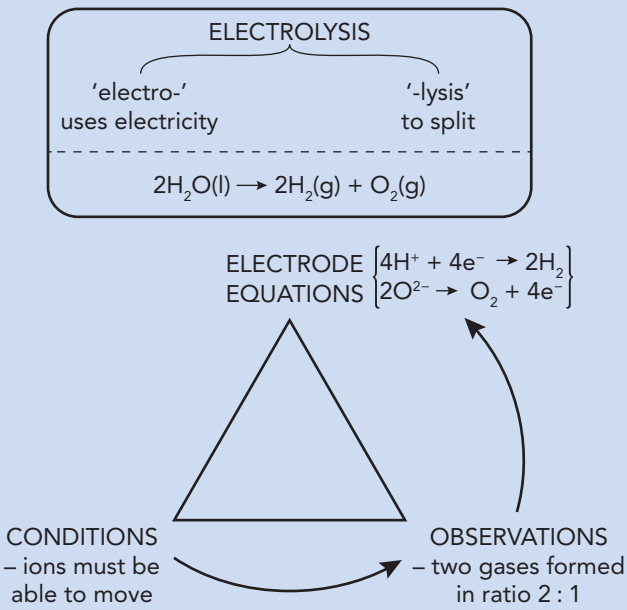

Figure C4.15: The electrolysis of water.

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SUMMARY

Metals can act as electrical conductors. Non-metallic materials (e.g. plastics and ceramics) can act as non-conducting insulators.
Electrolysis is the decomposition of an ionic compound by the passage of an electric current when the compound is molten or dissolved in aqueous solution.
A simple electrolytic cell has different components, such as the cathode, anode, liquid electrolyte and a power supply.
The electrode products of molten lead(II) bromide during electrolysis using inert graphite electrodes are lead and bromine.
It is possible to predict the products of electrolysis of other molten binary ionic compounds.
The products of the electrolysis of concentrated sodium chloride solution are hydrogen and chlorine. Electrolysis of dilute sulfuric acid solution produces hydrogen and oxygen.
During electrolysis, metals or hydrogen are formed at the negative electrode (cathode), and non-metals are formed at the positive electrode (anode).
Ionic half-equations can be constructed to show the reactions taking place at the anode and cathode during electrolysis.
The transfer of charge around the circuit during electrolysis consists of three distinct stages: the movement of electrons in the external wires, the transfer of electrons at the electrodes and the movement of ions in the electrolyte.
Different electrolysis products are formed when copper(II) sulfate solution is electrolysed depending on whether graphite or copper electrodes are used. These differences are shown in the electrolyte solution as well as the electrode reactions.
A hydrogen–oxygen fuel cell can be used to generate electricity from the reaction between hydrogen and oxygen. Water is the only product.
The hydrogen–oxygen fuel cell has advantages and disadvantages as an alternative to petrol engines in vehicles.

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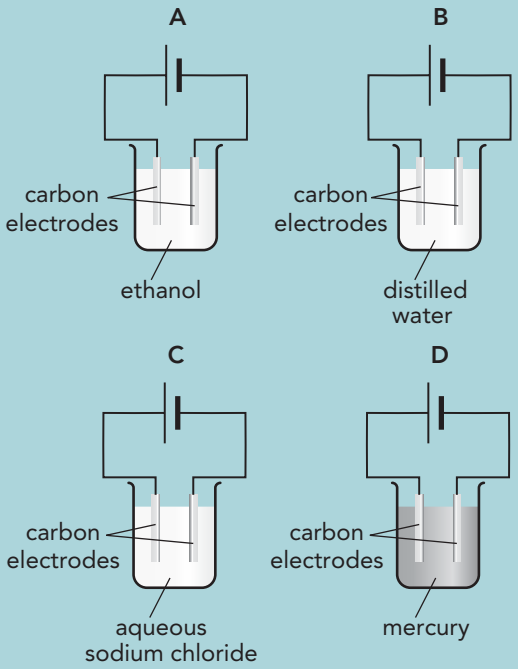
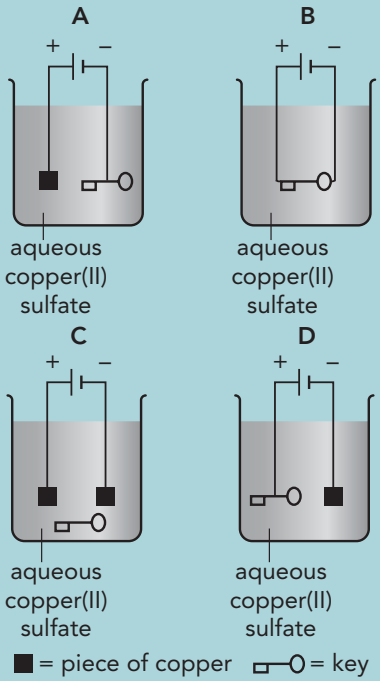
PRACTICE QUESTIONS

1 There are certain requirements for electrolysis to take place. One of these is the nature of the substance between the electrodes. **Determine** which of the diagrams A–D shows a beaker in which electrolysis takes place.



[1]

2 Electroplating is a common industrial process where metal is deposited onto an object using electrolysis. **Identify** which set of apparatus A–D would have a metal key coated with copper.



[1]

COMMAND WORD

determine: establish an answer using the information available.

COMMAND WORD

identify: name/select/recognise.

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CONTINUED

3 Seven substances A–G that all conduct electricity are listed here.

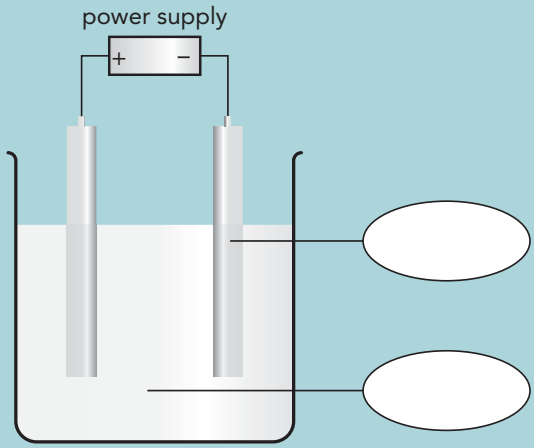
A aluminium
B chromium
C copper
D dilute sulfuric acid
E platinum
F molten sodium bromide
G sodium chloride solution

Identify the substance in A–G that:

a is used for inert electrodes in some electrolytic cells [1]
b produces a metal at the cathode when electrolysed [1]
c produces oxygen at the anode when electrolysed [1]
d is used in household electrical wiring. [1]

[Total: 4]

4 The figure shows an electrolytic cell.



a Complete the labels for the following:
i the electrode indicated [1]
ii the contents of the beaker. [1]

b **Sketch** arrows on the connecting wires to show the direction of the movement of electrons in the circuit. [1]

c Here is a list of three solutions.

dilute sulfuric acid **molten lead (II) bromide** **sodium chloride solution**

Identify the solution that would give a colourless gas at both electrodes during electrolysis. [1]

d The electrodes shown are inert. **Suggest** a suitable substance that they could be made from. [1]

[Total: 5]

COMMAND WORDS

sketch: make a simple freehand drawing showing the key features, taking care over proportions.

suggest: apply knowledge and understanding to situations where there is a range of valid responses in order to make proposals/put forward considerations.

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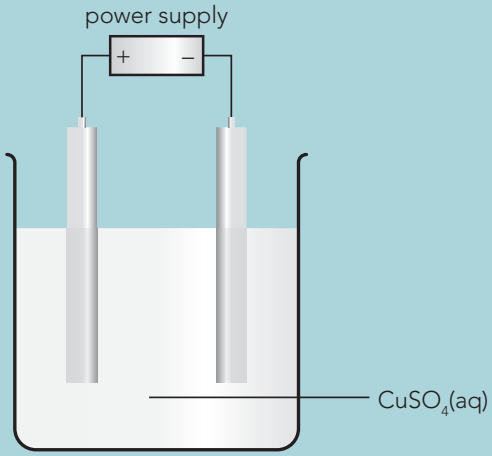
CONTINUED

5 The figure shows a cell for the electrolysis of copper(II) sulfate solution using inert electrodes.



a **State** what change in mass would take place at:

i the cathode [1]

ii the anode. [1]

b State what colour change would take place in the solution over time. [1]

c **Give** an ionic half-equation for the reaction at the positive electrode. [2]

The electrolysis is repeated using copper electrodes.

d State what difference would be observed in:

i the changes in the masses of the electrodes [4]

ii the change in colour of the solution. [2]

Explain your answer in each case.

e **Describe** how the charge is transferred between the electrodes. [2]

[Total: 13]

6 Hydrogen–oxygen fuel cells are described as being better for the environment than petrol cars.

a Explain how this is true. [1]

b Give *two* other differences between the use of hydrogen–oxygen fuel cells and petrol in cars. [2]

[Total: 3]

COMMAND WORDS

state: express in clear terms.

give: produce an answer from a given source or recall/memory.

explain: set out purposes or reasons/make the relationships between things clear/say why and/or how and support with relevant evidence.

describe: state the points of a topic/give characteristics and main features.

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SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
describe metals as electrical conductors and non-metallic materials as non-conducting insulators	C4.01			
define electrolysis and identify the components of a simple electrolytic cell	C4.01			
describe the electrolysis products of molten lead(II) bromide using graphite electrodes	C4.01			
describe the electrolysis of concentrated sodium chloride solution and dilute sulfuric acid using inert electrodes	C4.01			
predict the electrolysis products of other molten binary compounds	C4.01			
identify the products of the electrolysis of copper(II) sulfate solution using carbon or copper electrodes	C4.01			
describe how charge is transferred around the circuit involved in electrolysis	C4.01			
construct ionic half-equations for the ionic reactions taking place at the cathode	C4.01			
consider how a hydrogen–oxygen fuel cell generates electricity	C4.02			
describe the advantages and disadvantages of hydrogen–oxygen fuel cells as a means of powering road vehicles.	C4.02			

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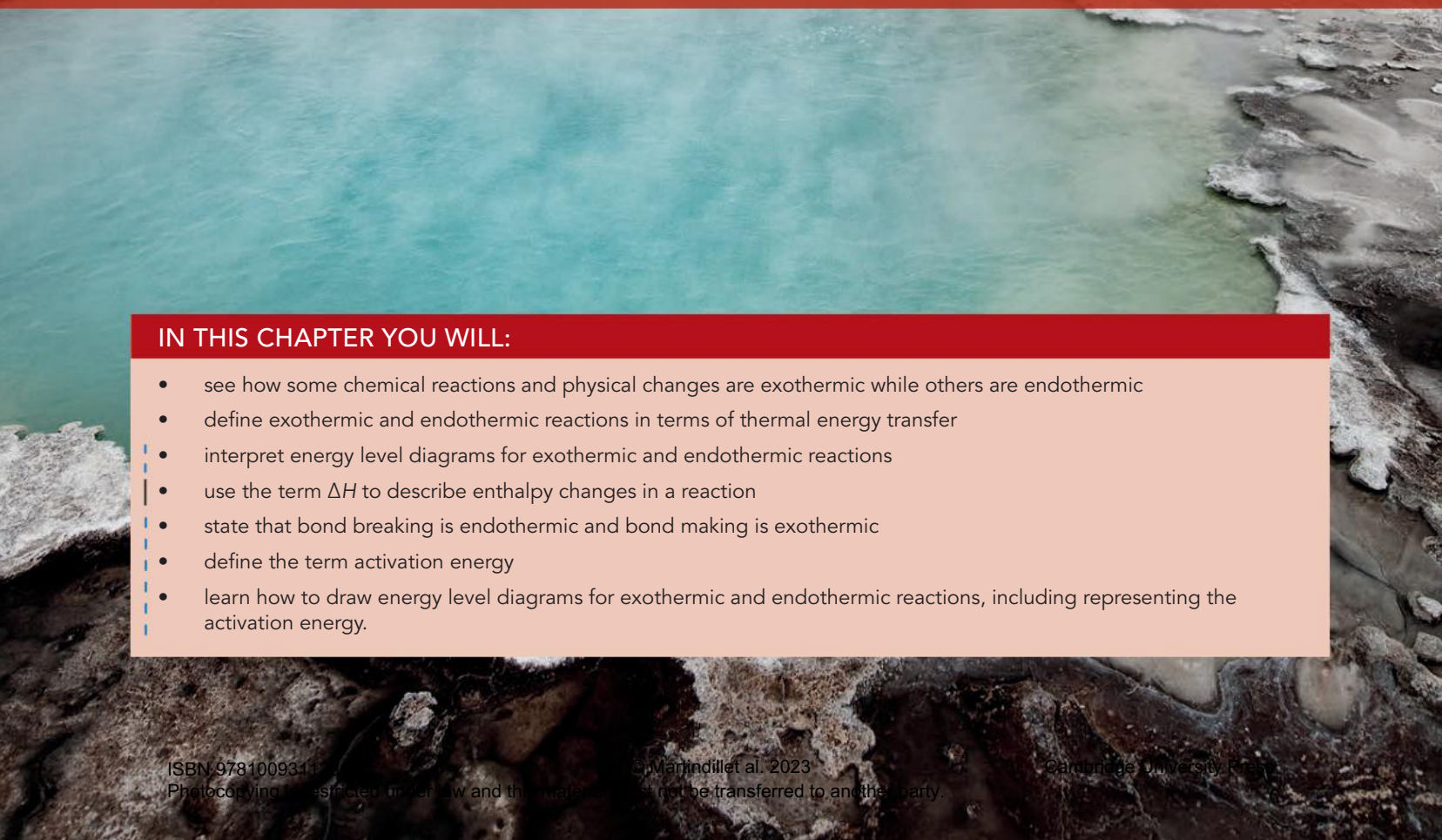
C5 Chemical energetics

All learners study some content in this chapter



IN THIS CHAPTER YOU WILL:

- see how some chemical reactions and physical changes are exothermic while others are endothermic
- define exothermic and endothermic reactions in terms of thermal energy transfer
- interpret energy level diagrams for exothermic and endothermic reactions
- use the term ΔH to describe enthalpy changes in a reaction
- state that bond breaking is endothermic and bond making is exothermic
- define the term activation energy
- learn how to draw energy level diagrams for exothermic and endothermic reactions, including representing the activation energy.

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BEFORE YOU START

Think back to the work that you have done on the different states of matter. How easy is it for matter to change from one state to another? Changing temperature has an obvious effect, but skiers and skaters will also know that pressure may turn solid ice into a film of liquid (Figure C5.01). Think about which of these changes of state require energy, and the reason for that energy being needed. Will the reverse changes give out energy?

Can you recall any other physical or chemical changes that give out heat? Briefly make a list of examples you can think of and share ideas with the whole class.

Figure C5.01: Skiing in powder snow.

SCIENCE IN CONTEXT C5.01

Keeping cool!

It is difficult to overestimate the importance of the invention of the modern refrigerator. The refrigerated transport and storage of food has led to important benefits in the home. Not only that, reliable refrigeration has led to the globalisation of markets and the availability of important commodities across, and between, continents.

A refrigerator (Figure C5.02) takes advantage of the heat energy changes linked to evaporation and condensation. The liquid coolant in the system is volatile and has a low boiling point. When it evaporates it absorbs heat from the surroundings (the inside of the fridge). The inside of the fridge and its contents are cooled down.

The coolant is pumped round the system. The vapour is compressed by the pump and condenses back to a liquid again. This gives out heat to the air behind the fridge. In this way, heat is transferred from the inside of the fridge out into the room and the contents are kept cold.

A similar evaporation–condensation cycle is used in modern air conditioners. The technology is now being applied in reverse to heat exchangers for domestic central heating and hot water systems. The use of such technology is aimed at reducing the energy demands and costs of modern homes to make them more environmentally sustainable.

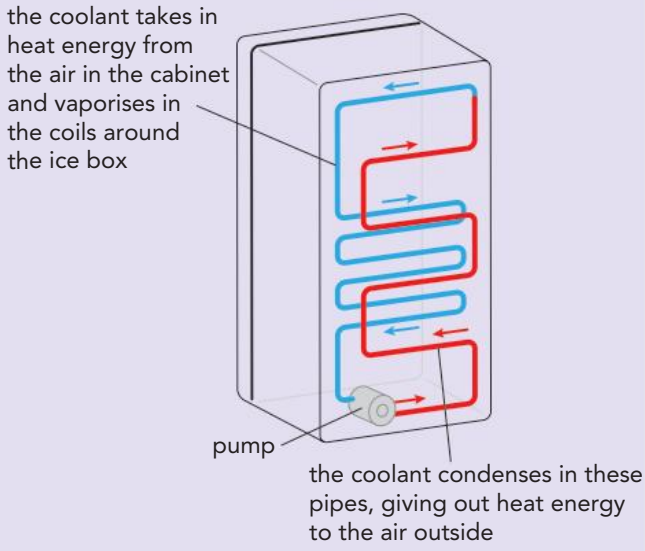

Figure C5.02: The evaporation–condensation cycle that works a refrigerator.

Discussion questions

1 Chlorofluorocarbons (CFCs) were used as the coolant in refrigerators and air conditioners, but their use has gradually been phased out. What environmental problems did they cause?

2 What were the benefits that refrigeration using coolants brought?

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C5.01 Exothermic and endothermic reactions

Energy can be transferred during a chemical reaction. This occurs due to the change in the chemical bonds during a reaction (a change in the chemical energy of the system). It is most often observed as a heat change (the reaction feeling warmer or cooler) although other observations, such as light being given out or a sound being produced, are also possible.

Many reactions, such as combustion (burning) give out heat energy. In some reactions, energy is absorbed. In one of the most important chemical reactions on the planet, plants use the energy in sunlight to convert carbon dioxide and water into carbohydrates by the process of photosynthesis (Figure C5.03).

Figure C5.03: Photosynthesis takes place in the green leaves of plants.

Processes that release heat energy (thermal energy) to the surroundings are called exothermic processes (Figure C5.04a). Adding zinc to copper(II) sulfate solution is an exothermic chemical reaction. The heat energy released in these exothermic reactions leads to an increase in the temperature of the surroundings and the reaction will feel hot. The surroundings include:

- the reaction mixture in the test-tube
- the air around the test-tube
- the test-tube itself
- the thermometer in the test-tube.

This final point is important: it is the thermal energy (heat) transferred to the thermometer that causes the rise in temperature shown on the thermometer.

Processes that take in heat energy from the surroundings are endothermic processes (Figure C5.04b).

Endothermic reactions absorb heat. The heat energy is taken in by the reacting substances (the system) and so leads to a decrease in the temperature of the surroundings. The reaction mixture will feel cold. When you try to remember these particular terms, concentrate on the first letters of the words involved:

- EXothermic means that heat EXits the reaction.
- ENdothermic means that heat ENters the reaction.

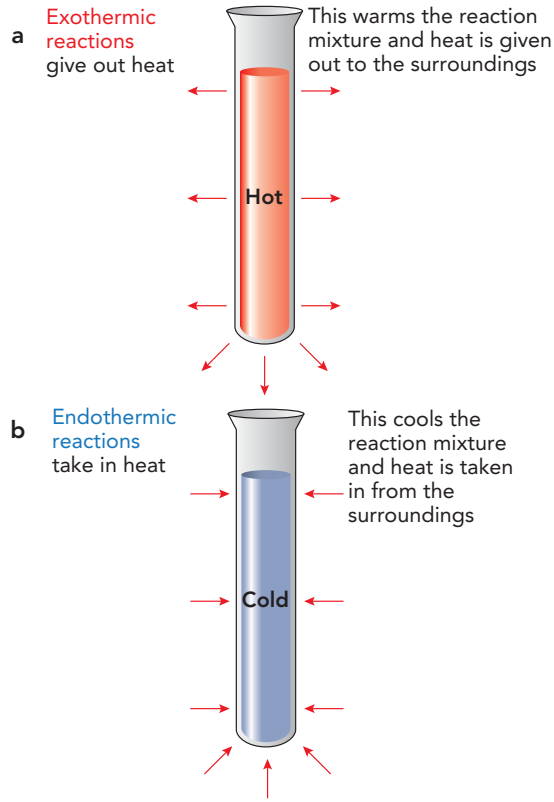

Figure C5.04 a: An exothermic reaction gives out heat energy to the surroundings. **b:** An endothermic reaction takes in thermal energy from the surroundings.

Energy level diagrams

Exothermic and endothermic changes for reactions can be shown using **energy level diagrams** (also called **reaction pathway diagrams**). Such diagrams show:

KEY WORDS

energy level diagram (reaction pathway diagram): a diagram that shows the energy levels of the reactants and products in a chemical reaction and shows whether the reaction is exothermic or endothermic.

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- the energy of the reactants and products on the vertical axis (*y*-axis)
- the 'reaction pathway' (progress of reaction) on the horizontal axis (*x*-axis), with reactants on the left and products on the right
- the energy change indicated by an arrow (upward or downward) between the reactants and products.

Methane is the simplest hydrocarbon molecule and the main component of natural gas. When it burns, it reacts with oxygen. The products are carbon dioxide and water vapour (water in the gaseous state):

methane + oxygen → carbon dioxide + water

$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g)$

Figure C5.05 shows an energy level diagram for the reaction of methane and oxygen producing carbon dioxide and water.

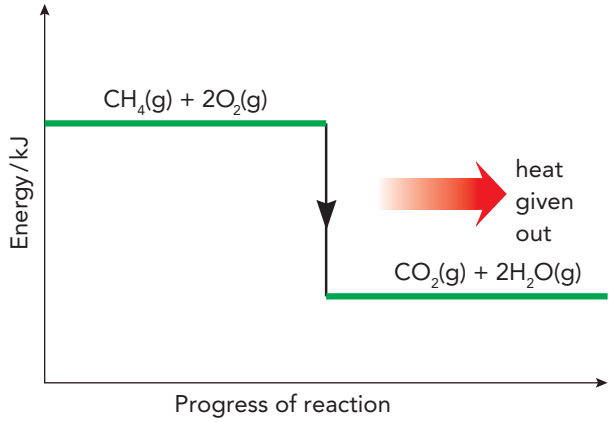


Figure C5.05: Energy level diagram for the exothermic reaction between methane and oxygen.

For an exothermic reaction you can see that:

- the energy of the reactants is higher than the energy of the products
- the black arrow points downwards to show that energy is given out (released).

The reaction between nitrogen and oxygen is endothermic. It is one of the reactions that take place when fuel is burnt in car engines.

The equation for this reaction is:

nitrogen + oxygen → nitrogen monoxide

$N_2(g) + O_2(g) \rightarrow 2NO(g)$

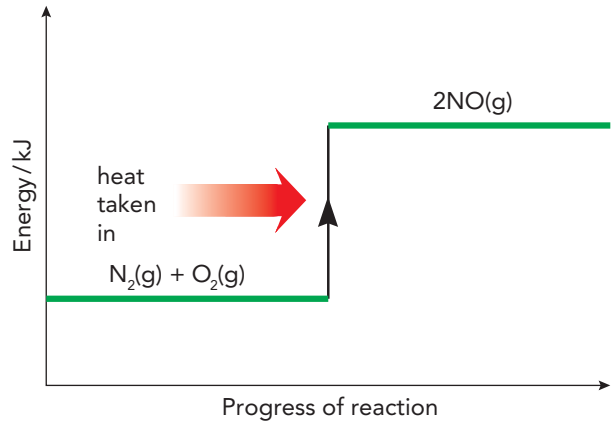


Figure C5.06: An energy level diagram for the reaction between nitrogen and oxygen.

Figure C5.06 shows an energy level diagram for this reaction.

For an endothermic reaction you can see that:

- the energy of the reactants is lower than the energy of the products
- the black arrow points upwards to show that energy is absorbed (taken in).

WORKED EXAMPLE C5.01

Magnesium burns in oxygen, giving off heat and light. Draw an energy level diagram to represent this reaction.

Step 1: Write a word equation for the reaction:

magnesium + oxygen → magnesium oxide

Step 2: Work out the formulae for the substances involved and write a balanced symbol equation for the reaction.

$Mg + O_2 \rightarrow MgO$

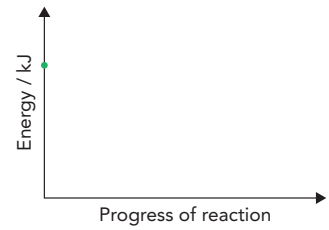
Balancing gives:

$2Mg + O_2 \rightarrow 2MgO$

Step 3: Identify whether energy is absorbed (endothermic) or released (exothermic).

The question tells us that energy is released as heat and light.

Step 4: Draw and label the axes.



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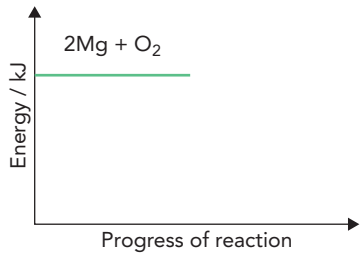
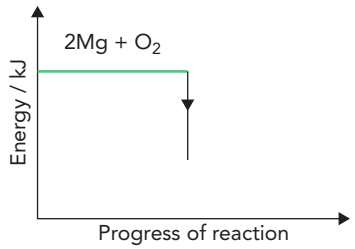
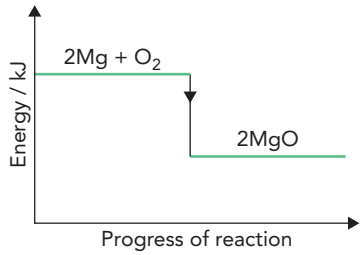
Step 5: Mark the reactants by drawing a horizontal line to the left-hand side of your axis. Write the reactants half of the balanced symbol equation on this line.



Step 6: As the reaction is exothermic, draw a downwards arrow from the reactants line to represent energy being released.



Step 7: Draw a horizontal line at the end of the arrow to represent the products. Label this with the products half of the balanced symbol equation.



Enthalpy and enthalpy change (ΔH)

The thermal energy (heat) content of a system is called the **enthalpy (H)** of the system. The transfer of thermal energy during a reaction is called the **enthalpy change (ΔH)** (the symbol Δ (delta) means 'change in') of the reaction.

- When heat is released from the system to the surroundings in an exothermic reaction, the enthalpy of the system decreases and ΔH is negative.
- When heat is taken in (absorbed) by the system from the surroundings in an endothermic reaction, the enthalpy of the system increases and ΔH is positive.

These ideas fit with the direction of the black arrows shown in the energy diagrams (Figures C5.05 and C5.06). The energy given out or taken in is measured in kilojoules (kJ). One kilojoule (1 kJ) = 1000 joules (1000 J). It is usually calculated per mole of a specific reactant or product (kJ/mol). The enthalpy change (ΔH) for the burning of methane is high (Figure C5.07). This high value explains why methane is such a useful fuel.

$$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g)$$

$$\Delta H = -728\ \text{kJ/mol}$$

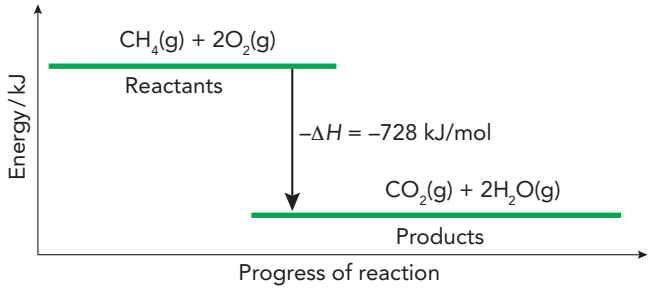


Figure C5.07: Detailed reaction pathway diagram for the exothermic reaction between methane and oxygen, showing the enthalpy change (ΔH).

Questions

C5.01 Which type of reaction takes in heat from its surroundings?

C5.02 **a** Draw an energy level diagram for the following reaction, which is exothermic.

$Zn(s) + CuSO_4(aq) \rightarrow ZnSO_4(aq) + Cu(s)$

b Label the enthalpy change for the reaction and state whether this will be positive or negative.

C5.03 What key features of an energy level diagram would indicate an endothermic reaction?

KEY WORDS

enthalpy (H): the thermal (heat) content of a system.

enthalpy change (ΔH): the heat change during the course of a reaction (also known as heat of reaction); can be either exothermic (a negative value) or endothermic (a positive value).

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Bond breaking and bond making

Most substances, apart from the noble gases (Group VIII), are involved in chemical bonding of some type (Chapter C2). During a reaction, some of the bonds between the particles are broken and new bonds are formed. During the reaction between methane and oxygen, as with all other reactions, bonds are first broken and then new bonds are made (Figure C5.08). In methane molecules, carbon atoms are covalently bonded to hydrogen atoms. In oxygen gas, the atoms are held together in diatomic molecules. During the reaction, all these bonds must be broken. As chemical bonds are forces of attraction between atoms or ions, breaking these bonds requires energy. Energy is needed to pull the atoms apart, so breaking chemical bonds takes in energy from the surroundings. Bond breaking is an endothermic process. New bonds are then formed: between carbon and oxygen to make carbon dioxide (CO_2), and between hydrogen and oxygen to form water (H_2O). Making these chemical bonds gives out energy to the surroundings. Bond making is an exothermic process.

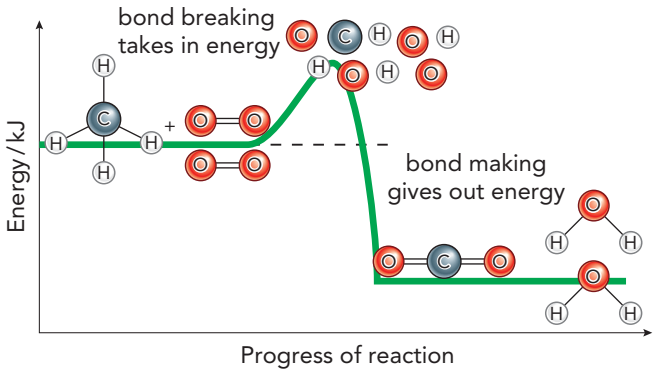

Figure C5.08: Reaction of methane with oxygen first involves the breaking of bonds in the reactants. This is followed by the formation of the new bonds of the products.

Some bonds are stronger than others. Stronger bonds have a higher **bond energy**. They require more energy to break, but they give out more energy when they are formed. In Figure C5.08 the bonds in the products are stronger than those in the reactants. This means more energy is given out when the new bonds form than is needed to break the original bonds. Overall, this reaction gives out thermal energy (heat). It is an exothermic reaction.

The relationship between making and breaking bonds and the energy involved is summarised in the memory aid 'MEXOBENDO': **M**aking bonds = **EXO**thermic and **B**reaking bonds = **ENDO**thermic (Figure C5.09).

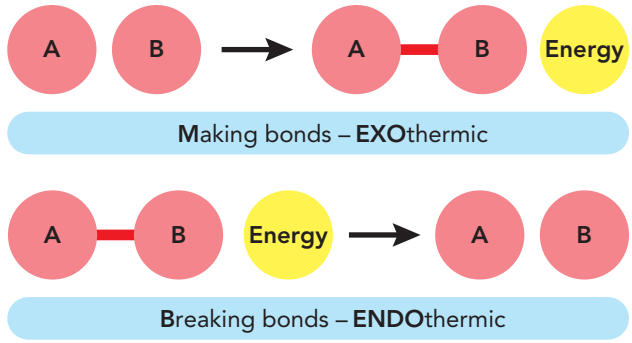

Figure C5.09: Memory aid for energy changes when making and breaking bonds: MEXOBENDO.

REFLECTION

How helpful do you find the memory aids such as 'EXothermic means that heat EXits the reaction; ENdothermic means that heat ENters the reaction' and 'MEXOBENDO'? Do you have a specific way to remember how to draw an energy level diagram?

What strategies could you use to help you learn the ideas about chemical energetics covered in this chapter?

Activation energy

Although the vast majority of reactions are exothermic, only a few are totally spontaneous and begin without help at normal temperatures (e.g. sodium or potassium reacting with water). More usually, additional energy is required to start the reaction. When fuels are burnt, for example, energy is needed to ignite them to start the reaction (Figure C5.10). This energy may come from a spark, a match or sunlight. It is called the **activation energy (E_a)**. It is required because initially some bonds must be broken before any new bonds can be formed. Once the reaction has begun, the energy released as new bonds are formed allows the reaction to continue.

KEY WORDS

bond energy: the energy required to break a particular type of covalent bond.

activation energy (E_a): the minimum energy required to start a chemical reaction; for a reaction to take place the colliding particles must possess at least this amount of energy.

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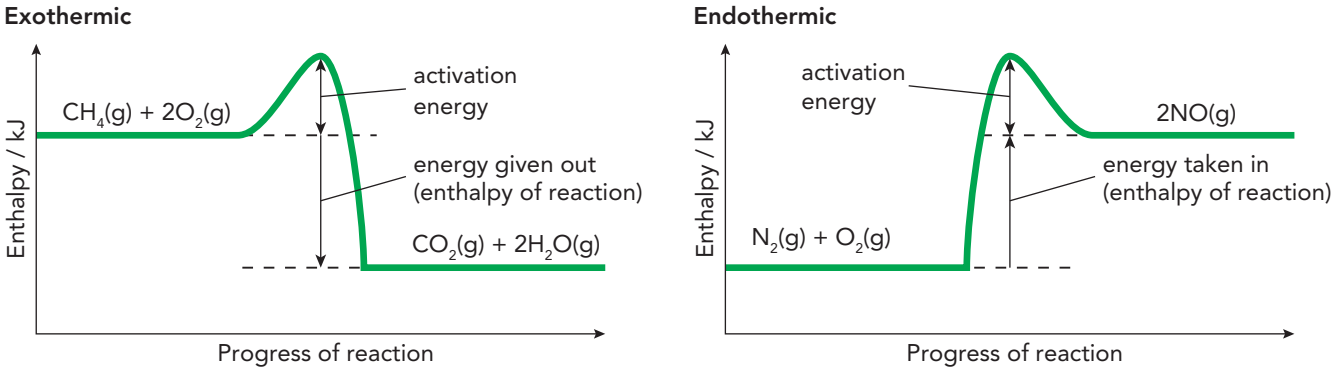

Figure C5.10: Energy level diagram for **a:** the burning of methane, and **b:** the formation of NO showing the need for activation energy to start the reaction.

Questions

C5.04 Is bond breaking an endothermic or an exothermic process?

C5.05 Hydrogen peroxide decomposes to produce water and oxygen. The equation is:

$$2H_2O_2(g) \rightarrow 2H_2O(g) + O_2(g)$$

Draw an energy level diagram for this reaction (there is a small amount of energy needed for this reaction to start).

C5.06 Explain why every chemical reaction must have an activation energy, even though for some reactions it may have a low value.

ACTIVITY C5.01

The chemical roller coaster

Have you noticed that energy level diagrams (reaction profiles) look a little bit like a roller-coaster ride? They go steeply up (taking in energy from the surroundings) and then there is a peak before they come racing down (releasing energy back into the surroundings as they do).

Using the exothermic reaction between hydrogen and oxygen, create a cartoon strip that explains the main stages in the energy level diagram (see Figure C5.11).

Think of the hydrogen and oxygen molecules being split into atoms before recombining to form water molecules.

Your cartoon strip should include:

- the key scientific words: activation energy, enthalpy change, exothermic, bond breaking, bond making
- at least five diagrams: start with just the reactants, then show the process of bond breaking, the activation energy (peak), the process of bond making and end with the products.

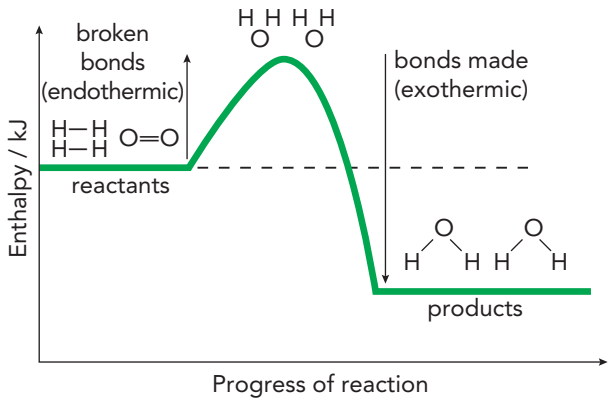

Figure C5.11: Energy level diagram for the reaction between hydrogen and oxygen.

You might want to see the reaction from the view of one of the atoms involved, giving them the stage to explain what is happening.

Peer assessment

With a partner, or in a small group, discuss your cartoon strips. Do they clearly show the progress of the reaction and the different processes involved? Assess the ideas in each other's cartoon strips to determine which individual diagrams best illustrate the different stages.

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PROJECT C5.01 MASTERMIND

Writing and answering questions is useful to help embed deeper levels of understanding of a given topic. You are therefore going to write a quiz for other members of your class. Can you write four rounds of different types of question?

Round 1: The warm-up. Write four simple questions worth one point. These should be either true/false, multiple choice or fill in the gap.

Round 2: What is that word? Look back through this chapter and identify four key words that you need to know the definition for. Look carefully at each definition to see whether the answer should be worth one or two points.

Round 3: Picture this. Provide a diagram with missing labels and ask for the labels to be completed. One point should be given for each label.

Round 4: Summing up. Set one or two questions that bring together multiple ideas. Think carefully about how points should be awarded based on the challenge of the questions.

All questions need to be based on materials covered in this chapter, but you must not repeat any questions in this coursebook. Plan your questions carefully. Ideally there should be an increasing level of difficulty. You will need to write out the answers to accompany your questions on a separate page.

In a group of up to four people, one person needs to be the quiz master and set their test for the other group members. You then need to award points. Once completed, you can swap the quiz master role and allow a different student to test people on the questions they wrote.

If you have time, why not, within your team, look at the sets of questions you have written and produce a master quiz with the questions you think test understanding of this chapter in the best way? You could even set this quiz for your teacher to complete!

SUMMARY

Some chemical and physical changes are exothermic, while others are endothermic.
An exothermic reaction transfers thermal energy to the surroundings, leading to an increase in the temperature of the surroundings.
An endothermic reaction takes in thermal energy from the surroundings, leading to a decrease in the temperature of the surroundings.
Energy level diagrams can be used to show the energy changes for both exothermic and endothermic reactions and show relative energies of reactants and products as well as the activation energy.
The overall energy change is known as the enthalpy change, ΔH. ΔH is negative for exothermic and positive for endothermic reactions.
Bond breaking is endothermic and bond making is exothermic.

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PRACTICE QUESTIONS

1 **Identify** which of the following statements best describes an endothermic reaction.

A The surroundings of the reaction get warmer.

B The reaction absorbs thermal energy.

C The reaction releases heat energy.

D The temperature of the reaction mixture increases. **[1]**

2 Both physical and chemical changes involve changes of energy.

Copy and complete the information in the table.

Process	Temperature change	Chemical or physical
water vapour changing to water		physical
salt solution to salt and water	increase	
magnesium plus hydrochloric acid		chemical
burning hydrogen to form water	increase	
iron rusting	increase	

[5]

3 The equation shows the reaction between sodium hydrogencarbonate and hydrochloric acid.

$$NaHCO_3 + HCl \rightarrow NaCl + CO_2 + H_2O$$

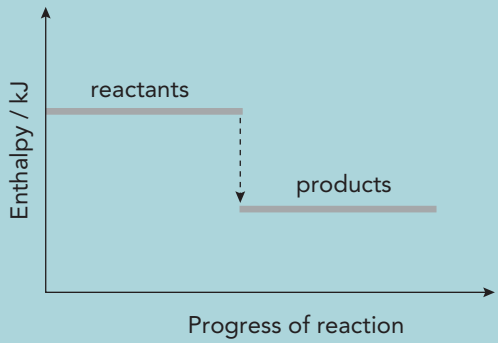
a **Suggest** an observation that is made as the reaction proceeds. **[1]**

At the beginning of the reaction the temperature of the acid is 21 °C. When the reaction is complete the temperature is 16 °C.

b **State** how you would know when the reaction has finished. **[1]**

c Is the reaction exothermic or endothermic? **Explain** your answer. **[2]**

A different carbonate is reacted with hydrochloric acid. The energy level diagram for this second reaction is shown in the figure.



d Is this reaction endothermic or exothermic? Explain your answer using ideas about energy. **[2]**

[Total: 6]

COMMAND WORD

identify: name/select/recognise.

COMMAND WORDS

suggest: apply knowledge and understanding to situations where there is a range of valid responses in order to make proposals/put forward considerations.

state: express in clear terms.

explain: set out purposes or reasons/make the relationships between things clear/say why and/or how and support with relevant evidence.

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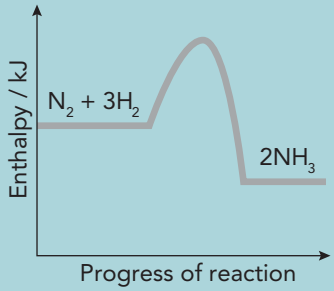
CONTINUED

4 Nitrogen reacts with hydrogen to form ammonia.

$$N_2 + 3H_2 \rightarrow 2NH_3$$

The figure shows the energy pathway diagram for the reaction between hydrogen and nitrogen. On the energy profile, label 'overall enthalpy change ΔH' and 'activation energy E_a'. **[2]**



SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
explain that some chemical reactions and physical changes are exothermic, while others are endothermic	C5.01			
state that an exothermic reaction transfers thermal energy to the surroundings, leading to an increase in the temperature of the surroundings	C5.01			
state that an endothermic reaction takes in thermal energy from the surroundings, leading to a decrease in the temperature of the surroundings	C5.01			
state that bond breaking is endothermic and bond making is exothermic	C5.01			
define activation energy	C5.01			
draw and interpret energy level diagrams for exothermic and endothermic reactions, including considering the activation energy for the reaction	C5.01			
draw and interpret energy level diagrams for exothermic and endothermic reactions, including considering the activation energy for the reaction and the enthalpy change for a reaction.	C5.01			

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C6

Chemical reactions

All learners study some content in this chapter

IN THIS CHAPTER YOU WILL:

- identify and understand the differences between physical and chemical changes
- describe the effects of various factors on the rate of a chemical reaction
- learn how to investigate the rates of various different reactions
- describe different practical equipment for investigating the rate of a reaction
- interpret data from rates experiments
- describe collision theory
- explain the effects of various factors on reaction rate using collision theory
- define redox reactions as those involving both oxidation and reduction
- define oxidation as the gain of oxygen and reduction as the loss of oxygen
- use Roman numerals to indicate oxidation number
- identify redox reactions and reduction and oxidation within these
- define oxidation as loss of electrons or increase in oxidation number
- define reduction as gain of electrons or decrease in oxidation number.

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BEFORE YOU START

Some chemical reactions are very fast and other reactions are slow (Figure C6.01).

Working in groups of two or three, discuss the following questions:

1 What reactions can you think of that are particularly slow?

2 What reactions can you think of that are particularly fast?

3 Think about reactions in the body, for instance, and occurrences such as the browning of sliced fruit open to the air. What is the most obvious thing that speeds up, or slows down, reactions?

Make notes and then join with the whole class to compare ideas.

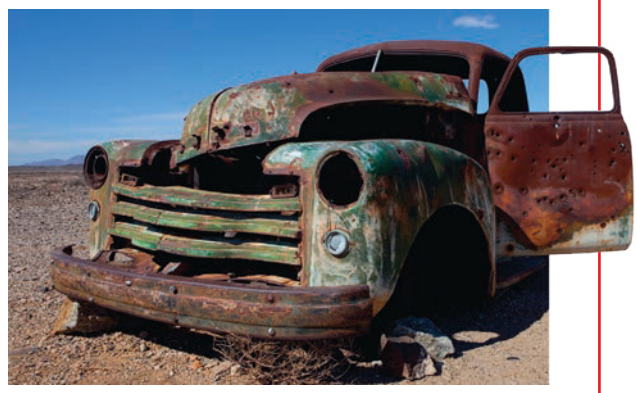

Figure C6.01: Rusting is a slow chemical reaction.

SCIENCE IN CONTEXT C6.01

Studying incredibly fast reactions

Ahmed Zewail, Linus Pauling Professor of Chemistry at the California Institute of Technology (Caltech), was the first Egyptian to win a Nobel Prize for science (Figure C6.02). He was awarded the 1999 Nobel Prize in Chemistry for his pioneering laser techniques that allow scientists to observe atoms while chemical reactions are taking place.

Zewail worked at Caltech for almost 40 years. During this time, he developed a way of observing chemical reactions despite the speed at which they occur – over a time scale of a millionth of a billionth of a second (a femtosecond = 10^{-12} seconds) – using ultrashort laser flashes. This field of reaction kinetics came to be known as femtochemistry. It allows scientists to observe and describe the changes taking place in reactions, and to analyse the short-lived transition states that occur as bonds in the reactants are broken and new bonds are made. Zewail's research paved the way for greater control over the result of chemical reactions, for new approaches to analysing chemical and biological reactions, as well as for faster electronics and ultra-precise machinery. Professor Zewail died in 2016, aged 70.

Figure C6.02: Professor Ahmed Zewail, in 1986, sometimes known as 'the father of femtochemistry'.

Discussion questions

1 Photosynthesis is a very fast series of biochemical reactions and has been described as the most significant reaction on Earth. Why do you think it is described as such? Can you suggest other possible reactions that could be described in this way?

2 Why do you think achieving the best possible rate of reaction is important in industry? What factors should be thought of when considering this?

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C6.01 Physical and chemical changes

The Chinese characters for 'chemistry' literally mean 'change study' (Figure C6.03). Chemistry deals with how substances react with each other. Chemical reactions range from the very simple through to the interconnecting reactions that keep our bodies alive.

But what is a chemical reaction? How does it differ from a simple physical change?

化学 huà xué

Figure C6.03: Chinese characters for Chemistry.

Physical changes

Ice, snow and water may look different, but they are all made of water molecules (H_2O). They are different physical forms of the same substance – water – existing under different conditions of temperature and pressure. One form can change into another if those conditions change (Chapter C1). In such physical changes, no new chemical substances are formed. Dissolving sugar in ethanol or water is another example of a physical change. It produces a solution, but the substances can easily be separated again by distillation (Chapter C12).

This is what we know about **physical changes**:

- In a physical change, the substances present remain chemically the same: no new substances are formed.
- Physical changes are often easy to reverse. Any mixtures produced are usually easy to separate.

Physical changes can involve heat energy. We saw in Chapter C1 that changing physical state involves heat being taken in or given out.

Chemical changes

Chemical changes are the result of chemical reactions. When magnesium burns in oxygen (Figure C6.04), the white ash produced is a new substance – the compound, magnesium oxide. Burning magnesium produces a brilliant white flame. Energy is given out in the form of heat and light. The combining of the two elements, magnesium and oxygen, to form the new compound is difficult to reverse.

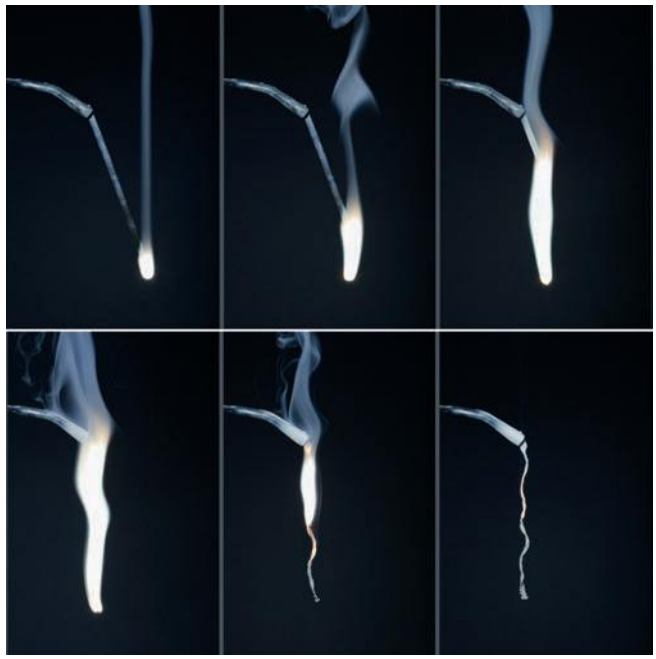

Figure C6.04: Magnesium burns strongly in air or oxygen, producing brilliant white light. As a result of this reaction, white magnesium oxide is formed.

Some other chemical reactions, such as those in fluorescent 'glow bracelets' (Figure C6.05), produce chemiluminescence. They give out energy in the form of light. The reaction between nitrogen and oxygen to make nitrogen monoxide is an example of another type of reaction. During this reaction, heat energy is taken in from the surroundings.

KEY WORDS

physical change: a change in the physical state of a substance or the physical nature of a situation that does not involve a change in the chemical substance(s) present.

chemical change: a change in which a new substance is formed.

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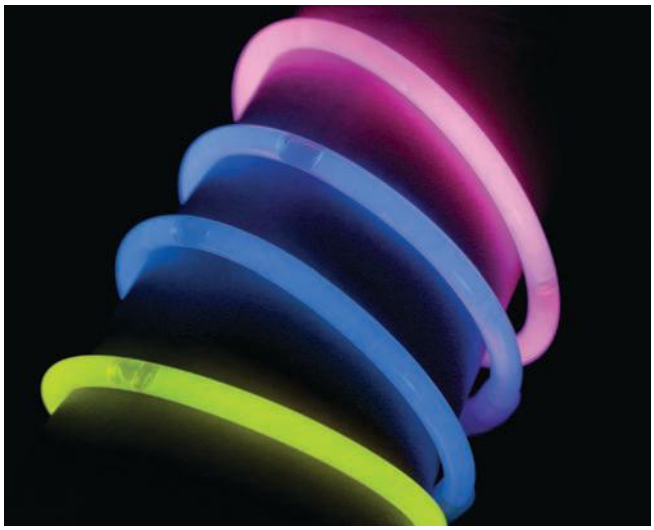

Figure C6.05: Glow-in-the-dark bracelets produce chemiluminescence.

This is what we know about chemical changes:

- The major feature of a chemical change, or reaction, is that new substance(s) are made during the reaction.
- Many reactions, but not all of them, are difficult to reverse.
- During a chemical reaction, energy can be given out (exothermic change) or taken in (endothermic change).

Questions

C6.01 State whether the following changes are physical or chemical:

- **a** melting of ice
- **b** burning of magnesium
- **c** evaporation of ethanol
- **d** dissolving of sugar in water

C6.02 State whether the following changes take in heat (are endothermic) or give out heat (are exothermic):

- **a** condensation of steam to water
- **b** burning of magnesium
- **c** addition of concentrated sulfuric acid to water
- **d** evaporation of a volatile liquid

C6.03 What is the most important thing that shows us that a chemical reaction has taken place?

C6.02 Rate of reaction

Any solid material that can burn in air will do so with a violence and speed that increases with the surface area of the material. An accidental spark from machinery or another source of ignition can lead to disastrous explosions in an environment with fine powders such as in flour mills (Figure C6.06a), sugar factories and wood mills. Even metal powders can produce quite spectacular effects (Figure C6.06b). Similarly, build-up of flammable gases such as methane can lead to dangerous explosions, and reactions with concentrated acids (see Chapter C7) can be very dangerous.

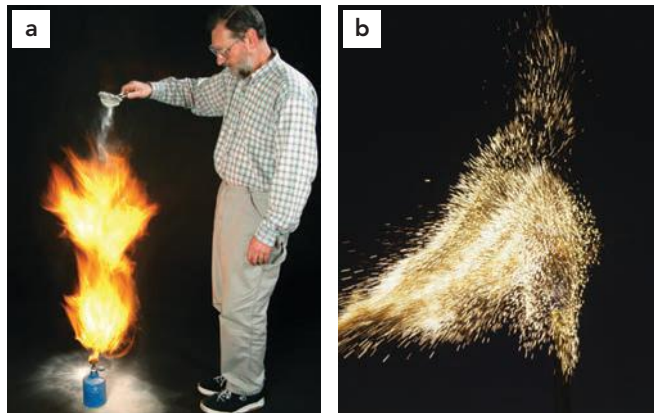

Figure C6.06 a: Fireball produced by dropping powdered flour into a flame. **b:** Iron dust ignited in a Bunsen flame.

What factors influence how fast a reaction occurs? Experiments have been carried out to study a wide range of reactions, and here we will consider the following major influences on the rate of a reaction (**reaction rate**):

- surface area of any solid reactants
- concentration of the reactant solutions
- pressure of gaseous reactions
- temperature at which the reaction is carried out
- presence of a **catalyst**.

KEY WORDS

reaction rate: a measure of how fast a reaction takes place.

catalyst: a substance that increases the rate of a chemical reaction but itself remains unchanged at the end of the reaction.

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Effect of surface area of reacting solids

Where one or more of the reactants is a solid, the more finely powdered (or finely divided) the solid(s) are, the greater the rate of reaction. This is because reactions involving solids take place on the surface of the solids. A solid has a much larger surface area when it is powdered than when it is in larger pieces (Figure C6.07).

A good demonstration of this is the reaction between limestone or marble chips (two forms of calcium carbonate) and dilute hydrochloric acid:

calcium carbonate + hydrochloric acid → calcium chloride + water + carbon dioxide

$$CaCO_3(s) + 2HCl(aq) \rightarrow CaCl_2(aq) + H_2O(l) + CO_2(g)$$

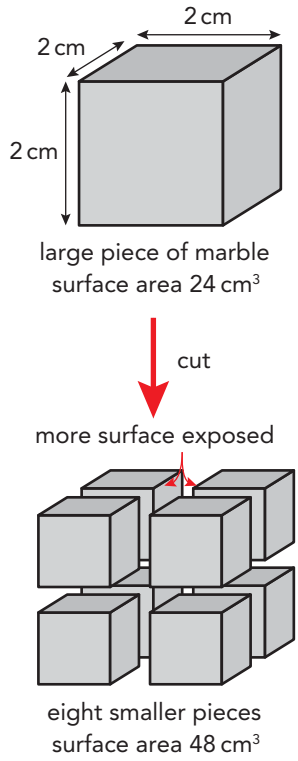

Figure C6.07: Breaking a cube into smaller pieces increases the surface area.

The experiment can be done as shown in Figure C6.08. Using this arrangement, we can compare two samples of marble chips, one sample (**B**) being in smaller pieces than the other sample (**A**).

Figure C6.08: Apparatus for experiments **A** and **B:** the reaction of marble chips with dilute hydrochloric acid.

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The experiment is carried out twice, once with sample **A** and once with sample **B**. In each experiment the mass of sample used is the same. The same volume and concentration of hydrochloric acid is used in both experiments. The flask is placed on the balance during the reaction. The flask will lose mass during the reaction as the carbon dioxide escapes. The balance is set to zero (tared) as the stopclock is started. Mass readings are taken at regular time intervals and the loss in mass can be calculated. When the loss in mass is plotted against time, curves such as those in Figure C6.09 are obtained.

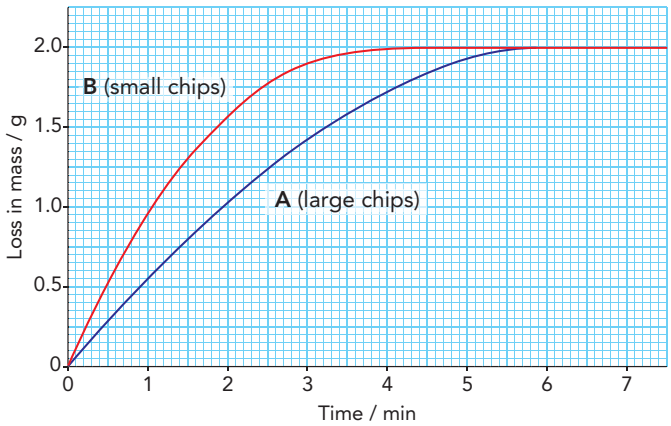

Figure C6.09: The graph shows the loss in mass against time for experiments **A** and **B**. The reaction is faster if the marble chips are broken into smaller pieces (curve **B**).

There are important points about the graph.

1. The reaction is fastest at the start. This is shown by the steepness of the curves over the first few minutes. Curve **B** is steeper than curve **A**. This means that gas (CO_2) is being produced faster with sample **B**, the one with the larger surface area. As the reaction proceeds, both reactions slow down as the reactants are used up (Figure C6.10).
2. The total volume of gas released is the same in both experiments as the mass of $CaCO_3$ and the amount of acid are the same in both cases.
3. A numerical value for the rate of reaction at any given time can be found by drawing a tangent to the curve at that time. The slope of that tangent gives a value for the rate of reaction at that point. A tangent drawn at the start of the curve will give the initial rate of reaction.

These results show that the rate (speed) of a reaction increases when the surface area of a solid reactant is increased.

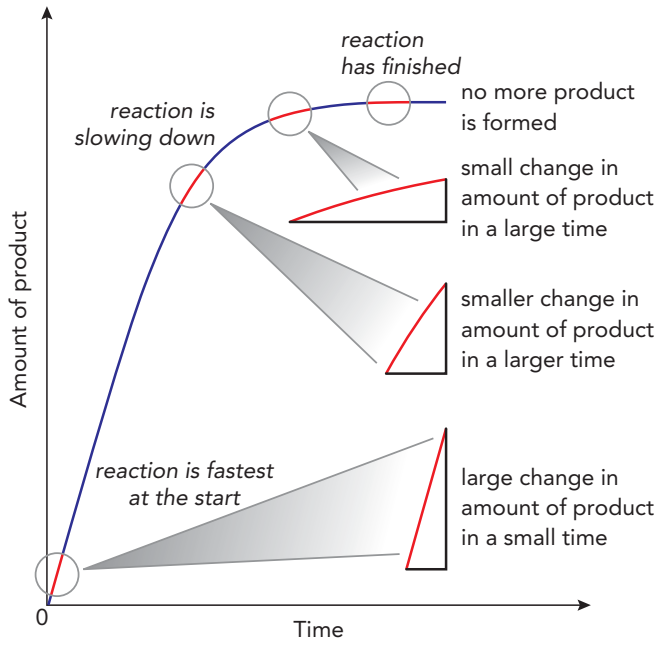

Figure C6.10: A chemical reaction is fastest at the start. It slows down as the reactants are used up.

Effect of concentration of reacting solutions

Reactions that produce gases are also very useful in studying the effect of solution concentration on the reaction rate. The reaction between marble chips and acid can be adapted for this (Figure C6.11).

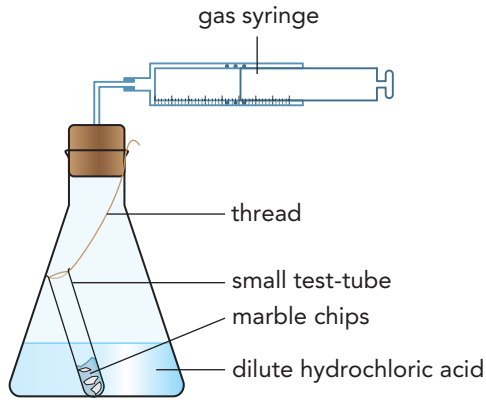

Figure C6.11: Recording the production of a gas using a gas syringe.

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As in the previous experiment, we will compare two different situations. The volume of acid, the temperature and the mass of marble chips used will be the same in both experiments, but the concentration of acid will change. The thread holding the test tube allows the marble chips to be added quickly with very little loss of gas.

The acid in experiment **C** is twice as concentrated (1.0 mol/dm^3) as in experiment **D** (0.5 mol/dm^3). The carbon dioxide gas produced is collected in a gas syringe. The volume of gas produced is measured at frequent time intervals. We can then plot a graph of volume of gas collected against time, like the one in Figure C6.12.

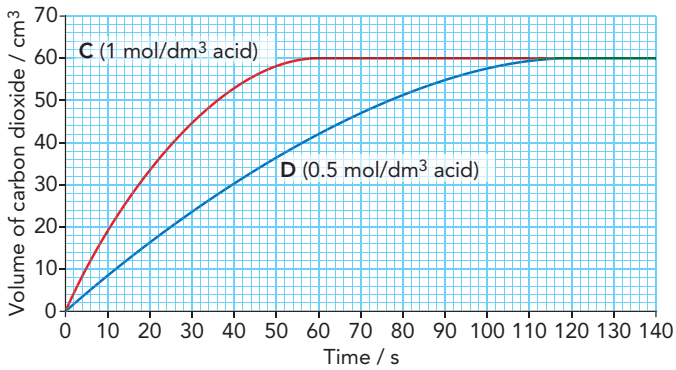

Figure C6.12: Graph showing the volume of carbon dioxide collected in experiments **C** and **D**.

Again, the graph shows some important points.

1 The curve for experiment **C** is steeper than for **D**. This shows clearly that reaction **C**, using more concentrated acid, is faster than reaction **D**.

2 The curve for experiment **C** starts off twice as steeply as for **D**. This means that the reaction in **C** is twice as fast as in experiment **D** initially. So, doubling the concentration of the acid doubles the rate of reaction.

3 The total volume of carbon dioxide produced is the same in both experiments. Both reactions produce the same volume of gas, although experiment **C** produces it faster.

These results show that the rate of a reaction increases when the concentration of a reactant in solution is increased.

Effect of pressure of reacting gases

Another type of reaction that shows the effect of concentration on reaction rate are reactions involving gases. In a reaction involving gases, increasing the pressure has a similar effect to increasing the concentration in a liquid and the rate of reaction will increase. Changing the pressure on a reaction that involves only solids or liquids does not affect the reaction rate. One reaction that shows the effect of increasing the pressure is the combustion of fuel in a car engine. Such a reaction explosively generates energy. The reaction is that of the hydrocarbons in petrol (gasoline) burning with the oxygen in the air as they are compressed by the movement of the piston (Figure C6.13).

The gases are ignited by the spark plug. The resulting explosion drives the piston down and that movement is transmitted to the wheels of the car. The exhaust gases are ejected through the exhaust valve.

Figure C6.13: Computer graphic of the explosion within the cylinder of a petrol engine as the piston compresses the gases.

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REFLECTION

The effects of solution concentration, solid surface area and gas pressure on reaction rate have been grouped together here because they are all 'concentration' related. Does emphasising relationships between ideas help you understand different concepts in chemistry? Could you explain the effect of concentration on the rate of reaction to someone else using these relationships? Why or why not?

Effect of temperature

A reaction can be made to go faster or slower by changing the temperature of the reactants. Some food is stored in a refrigerator because the food decays more slowly at lower temperatures.

To study the effect of temperature on rate of reaction we can look at the reaction between sodium thiosulfate and hydrochloric acid. In this case, the formation of a precipitate is used to measure the rate of reaction (experiment **E**).

sodium thiosulfate + hydrochloric acid → sodium chloride + sulfur + sulfur dioxide + water

$$Na_2S_2O_3(aq) + 2HCl(aq) \rightarrow 2NaCl(aq) + S(s) + SO_2(g) + H_2O(l)$$

The experimental setup is shown in Figure C6.14.

A cross is marked on a piece of paper. A flask containing sodium thiosulfate solution is placed on top of the paper. Hydrochloric acid is added quickly. The yellow precipitate of sulfur produced is very fine and stays suspended in the liquid. With time, as more and more sulfur is formed, the liquid becomes cloudier and more difficult to see through. The time taken for the cross to 'disappear' is measured. The faster the reaction, the shorter the length of time during which the cross is visible.

Experiment **E** is carried out several times with solutions pre-warmed to different temperatures. The solutions and conditions of the experiment must remain the same; only the temperature is altered. A graph can then be plotted of the time taken for the cross to disappear against temperature, like that shown in Figure C6.15a.

The graph shows two important points.

1 The cross disappears more quickly at higher temperatures. The shorter the time needed for the cross to disappear, the faster the reaction.

2 The curve is not a straight line.

As rate of reaction = $\frac{1}{\text{time}}$, a graph of $\frac{1}{\text{time}}$ against temperature would show how the rate increases with a rise in temperature (Figure C6.15b).

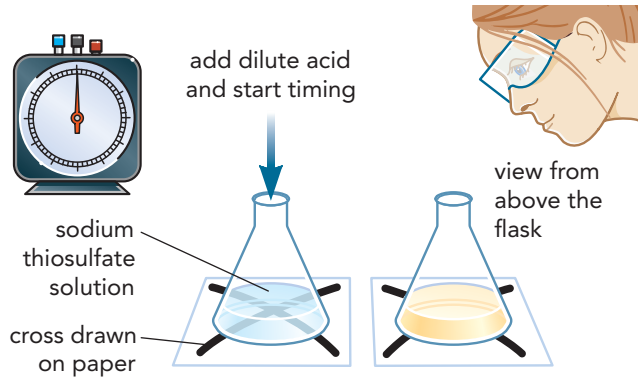

Figure C6.14: Apparatus for the reaction between hydrochloric acid and sodium thiosulfate (experiment **E**).

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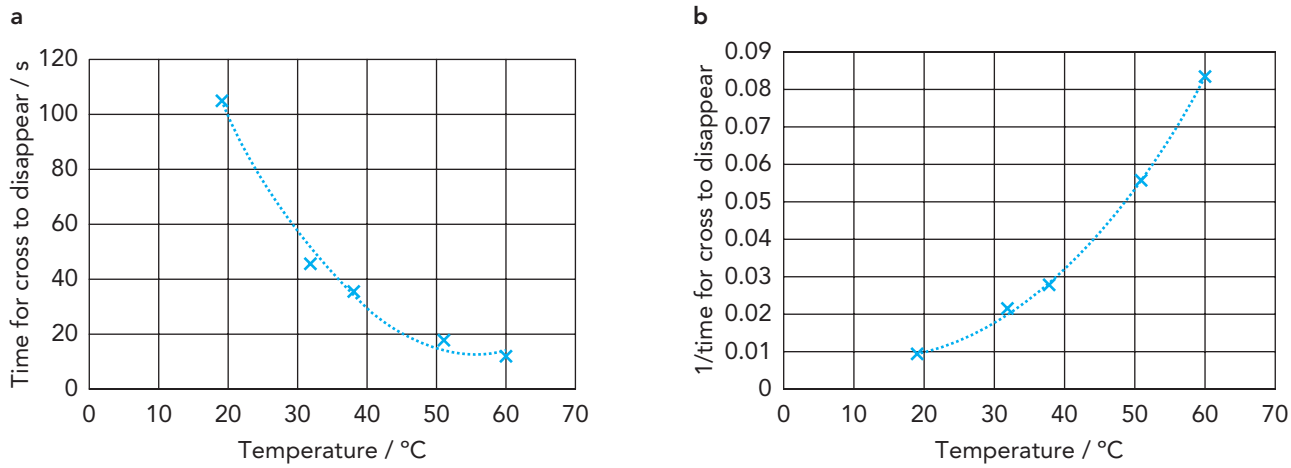

Figure C6.15 a and b: Graphs for experiment **E** on the reaction between hydrochloric acid and sodium thiosulfate.

Presence of a catalyst

Hydrogen peroxide is a colourless liquid with the formula H_2O_2. It is a very reactive oxidising agent. Hydrogen peroxide decomposes to form water and oxygen:

hydrogen peroxide → water + oxygen

$2H_2O_2(l) \rightarrow 2H_2O(l) + O_2(g)$

We can follow the rate of this reaction by collecting the oxygen in a gas syringe (Figure C6.16a). The formation of oxygen is very slow at room temperature. However, the addition of powdered manganese(IV) oxide (MnO_2) makes the reaction go much faster (experiment **F**).

The black powder does not disappear during the reaction. Indeed, if the solid is filtered and dried at the end of the reaction, the same mass of powder remains (Figure C6.16b). We say that manganese(IV) oxide is a catalyst for this reaction; it speeds up the reaction whilst remaining unchanged at the end.

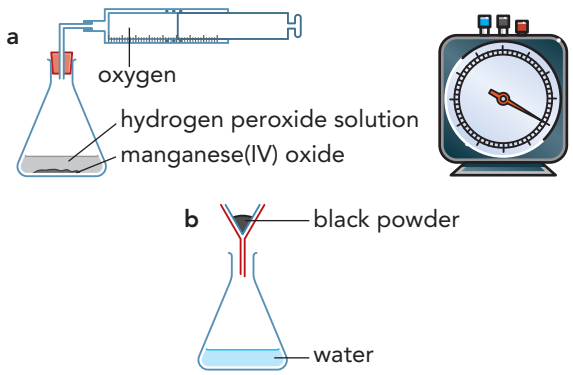

Figure C6.16 a: Apparatus for the experiments on the decomposition of hydrogen peroxide to water and oxygen. **b:** The black powder does not disappear during the reaction.

Questions

C6.04 What will we observe happening to the rate of a chemical reaction in response to the following?

- **a** an increase in temperature
- **b** an increase in the surface area of a solid reactant
- **c** an increased concentration of a reacting solution

C6.05 Why is perishable food kept in a refrigerator?

C6.06 What happens to the rate of a reaction over time, i.e. as the reaction progresses?

C6.07 What is a catalyst?

ACTIVITY C6.01

Planning and design of an experiment

Working in your practical group, plan and design an experiment to find which of three possible solid catalysts, A, B or C, works best to catalyse the formation of oxygen from a dilute solution of hydrogen peroxide. You may find that the information in Chapter C12 is useful for this activity. Also, think about other experiments you have performed.

Your plan should include a safety note, the equipment and chemicals required, the method to be followed, and how the results will be analysed (see experiments E and F).

Hydrogen peroxide decomposes to form water and oxygen.

hydrogen peroxide → water + oxygen

$2H_2O_2 \rightarrow 2H_2O + O_2$

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CONTINUED

This reaction is very slow at room temperature but can be speeded up by using a catalyst. You have access to three possible catalysts, a dilute solution of hydrogen peroxide, and normal laboratory apparatus. The comparison must be a 'fair test' (only one variable should be changed, the others kept constant) and consider the relevant factors that influence the rate of a reaction.

When you have planned your method, come back together as a class and compare notes, discussing the merits of the different approaches taken.

Peer assessment

Swap your plan with another group. Have they . . .

- included a safety note?
- included the equipment and chemicals required?
- included a clear method that is easy to follow?
- said how the results will be analysed?

Write down one thing the group did well and one thing they could improve on next time they design an experiment.

Collision theory of reaction rate

Collision theory allows us to think about the effect of each of the factors outlined previously in terms of what the particles are doing. These ideas are used to explain the effects described.

KEY WORDS

collision theory: a theory that states that a chemical reaction takes place when particles of the reactants collide with sufficient energy to initiate the reaction.

Collision frequency

Surface area, concentration and pressure

The importance of surface area in reactions involving solids helps us understand how reactions take place. In these cases, reactions can only occur when particles collide with the surface of a solid. If a solid is broken into smaller pieces, there is more surface exposed. This means there are more places where collisions can happen and so there is more chance of a reaction taking place. Iron reacts more readily with oxygen if it is powdered (Figure C6.17).

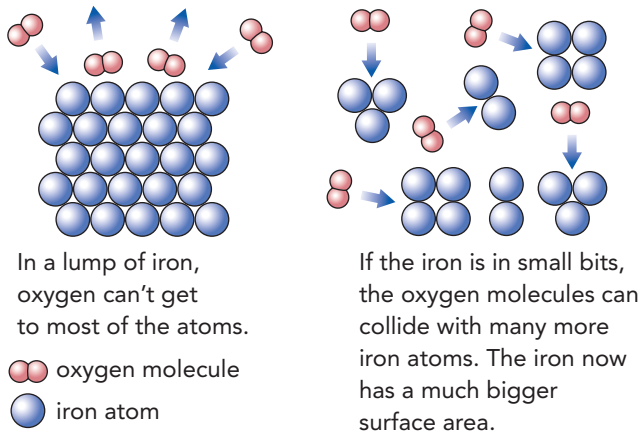

Figure C6.17: The reaction between iron and oxygen is speeded up if the iron is in small pieces.

We can see how these ideas (collision theory) apply in other situations. When solutions are more concentrated, the speed of a reaction is faster. A more concentrated solution means that there are more reactant particles in a given volume (a unit volume). Collisions will occur more often. The more often they collide, the more chances the particles have to react. This means that the rate of a chemical reaction will increase if the concentration of the reactants is increased. A more concentrated acid reacts more vigorously with a piece of magnesium ribbon than a dilute acid (Figure C6.18). The increased acid concentration means that the frequency of collision between the H^+ ions and the metal creates a greater chance of the reaction occurring.

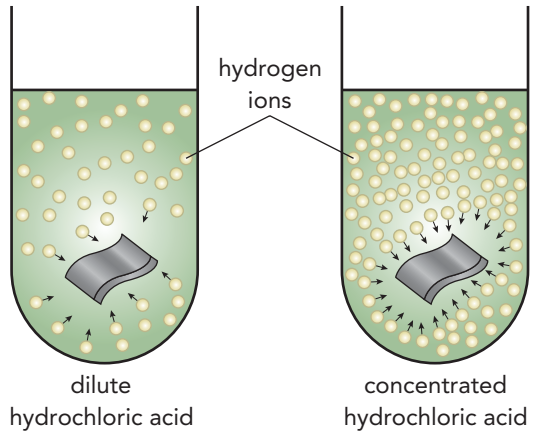

Figure C6.18: The more concentrated the acid solution, the faster the reaction with the magnesium.

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For reactions involving gases, increasing the pressure has the same effect as increasing the concentration, so the rate of a reaction between gases increases with pressure (Figure C6.19).

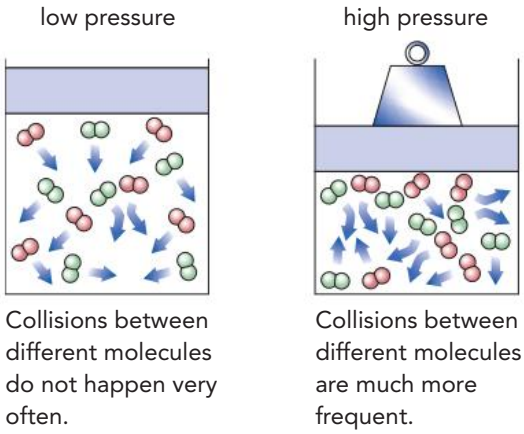

Figure C6.19: Increasing the pressure of gases effectively increases the concentration of the gas.

Temperature

When the temperature is raised, a reaction takes place faster. At higher temperatures, the particles have more kinetic energy and are moving faster. Again, this means that collisions will occur more often, giving more chance of reaction. Also, the particles have more energy at the higher temperature. This increases the chances that a collision will result in bonds in the reactants breaking and new bonds forming to make the products. If we look at the reaction between zinc and hydrochloric acid, we can see how the rate of reaction is affected by changes in collision frequency (Figure C6.20).

Activation energy

Not every collision between particles in a reaction mixture produces a reaction. We have seen in Chapter C5 that a certain amount of energy is needed to begin to break bonds in the reactant molecules. This minimum amount of energy is known as the activation energy (E_a) of the reaction.

- Each reaction has its own different value of activation energy.
- When particles collide, they must have a combined energy greater than this activation energy, otherwise they will not react.
- Chemical reactions occur when the reactant particles collide with each other.

There are two factors that explain why an increase in temperature increases the rate of a reaction.

1. The increased temperature means that the molecules are moving faster and therefore they collide more often. The frequency of collision is increased and so the rate of reaction is faster.
2. At the higher temperature, the particles have higher kinetic energy. This means that when they collide, more particles will have the minimum amount of energy needed to react. At the higher temperature more of the collision will produce a reaction; there will be more successful collisions. The number of effective collisions increases with increasing temperature.

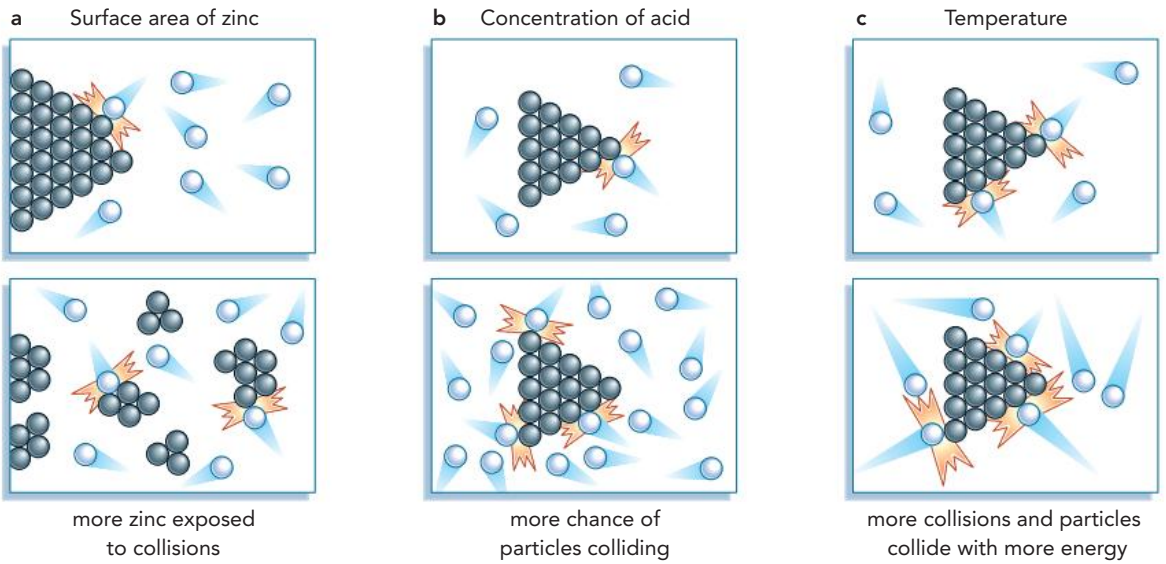

Figure C6.20: Collision theory can be used to explain how various factors affect the rate of reaction. Here we use the reaction between zinc and hydrochloric acid as an example.

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The second factor is the more important of the two in explaining the level of increased rate produced by raising the temperature of a reaction.

Action of a catalyst

A catalyst increases the rate of reaction by reducing the amount of energy that is needed to break the bonds. This reduces the activation energy of the reaction and makes sure that more collisions are likely to produce products. The rate of the reaction is therefore increased. The catalyst remains chemically unchanged at the end of the reaction. Because it is unchanged, a catalyst can be reused.

We can think of an 'analogy' for this. Suppose we are hiking in the mountains (Figure C6.21). We start on one side of a mountain and want to get to the other side. We could go right over the summit of the mountain. This would require us to be very energetic. What we might prefer to do would be to find an alternative route along a pass through the mountains. This would be less energetic. In our analogy, the starting point corresponds to the reactants and the finishing point to the products. The route over the top of the mountain would be the uncatalysed path. The easier route through the pass would be a catalysed path.

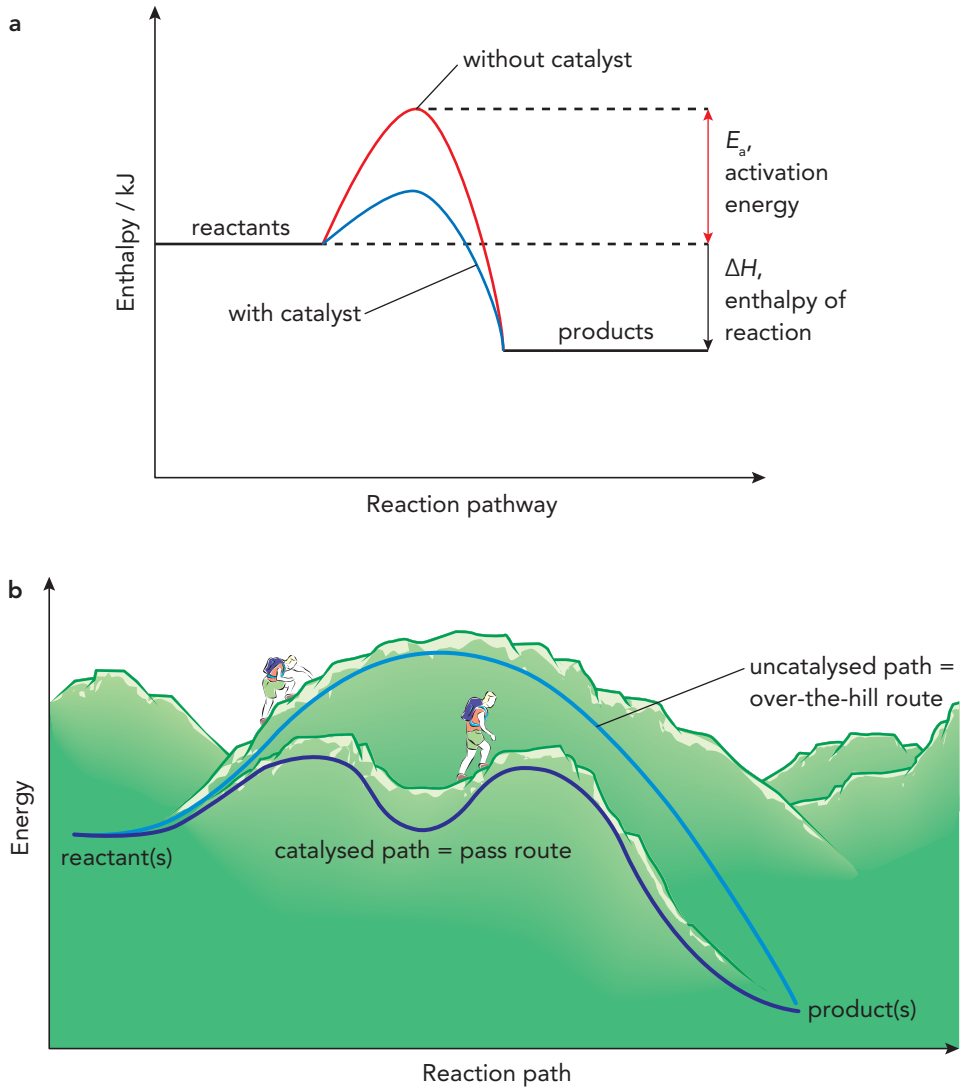

Figure C6.21 a: The reaction pathway diagram for an exothermic reaction showing how a catalyst lowers the activation energy of the reaction. **b:** The barrier between reactant(s) and product(s) may be so high that it defeats all but the most energetic; the catalysed route is an easy pass through the mountains.

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Different chemical reactions need different catalysts. One broad group of catalysts works by adsorbing molecules onto a solid surface. This process of **adsorption** brings the molecules of reactants closer together. The process of adsorption is also thought to weaken the bonds in the reactant molecules. This makes them more likely to react. Some of the most important examples of industrial catalysts work in this way, for example iron in the Haber process and vanadium(V) oxide in the Contact process. The efficiency of the solid catalysts in the Haber and Contact processes is improved by increasing the surface area of catalyst available to interact with the gaseous reactants.

KEY WORD

adsorption: the attachment of molecules to a solid surface.

Questions

C6.08 Does the presence of a catalyst increase or decrease the activation energy for a reaction?

C6.09 In terms of the collision theory, explain why the rate of a reaction increases with:

- **a** an increase in temperature
- **b** an increase in the surface area of a solid reactant
- **c** an increased concentration of a reacting solution.

C6.03 Redox reactions

Combustion, oxidation and reduction

Combustion reactions are of great importance and can be very useful or destructive. The combustion of natural gas is an important source of energy for homes and industry. Natural gas is mainly methane. The complete combustion of methane produces carbon dioxide and water vapour:

$$\text{methane} + \text{oxygen} \rightarrow \text{carbon dioxide} + \text{water}$$

$$CH_4(g) + 2O_2(g) \rightarrow CO_2 + 2H_2O(g)$$

In combustion reactions, the substance being combusted is oxidised. Oxygen is added and oxides are formed. For example, when air is passed over heated copper, the surface becomes coated with black copper(II) oxide (Figure C6.22a):

$$\text{copper} + \text{oxygen} \xrightarrow{\text{heat}} \text{copper(II) oxide}$$

$$2Cu + O_2 \xrightarrow{\text{heat}} 2CuO$$

This process can be reversed, and the copper surface regenerated, if hydrogen gas is passed over the heated material. The black coating on the surface turns pink as the reaction takes place (Figure C6.22b):

$$\text{copper(II) oxide} + \text{hydrogen} \xrightarrow{\text{heat}} \text{copper} + \text{water}$$

KEY WORD

combustion: a chemical reaction in which a substance reacts with oxygen; the reaction is exothermic.

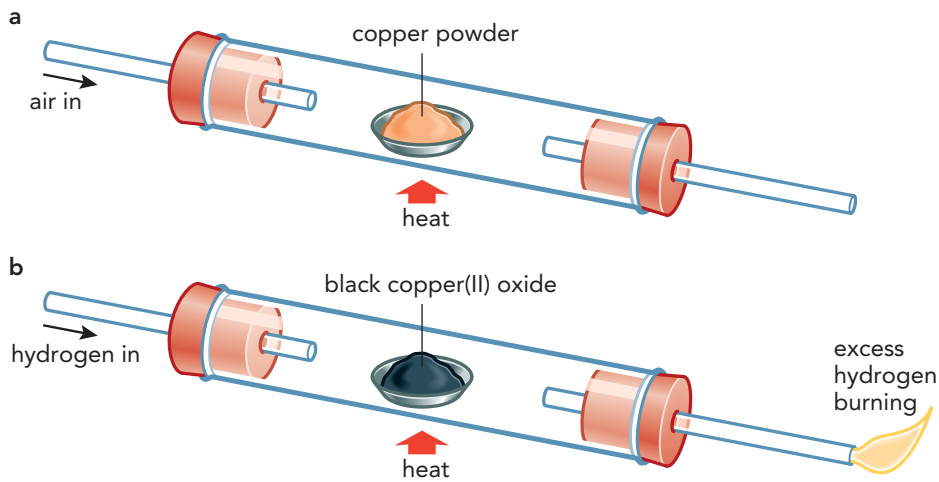

Figure C6.22 a: Oxidation of copper to copper(II) oxide. **b:** Reduction of copper(II) oxide back to copper using hydrogen.

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During this reaction, the copper(II) oxide is losing oxygen. The copper(II) oxide is undergoing reduction. It is losing oxygen and being reduced (Figure C6.23). The hydrogen is gaining oxygen; hydrogen is being oxidised.

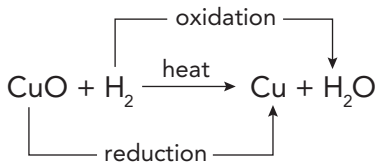

Figure C6.23: Reduction of copper(II) oxide with hydrogen.

It is important that you notice the words we use in describing these reactions:

- If a substance gains oxygen during a reaction, it is *oxidised*.
- If a substance loses oxygen during a reaction, it is *reduced*.

Notice that the two processes of oxidation and reduction take place together during the same reaction.

Consider the following reaction (Figure C6.24):

zinc oxide + carbon → zinc + carbon monoxide

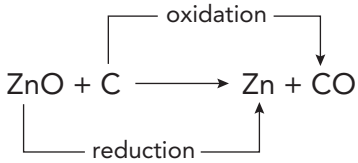

Figure C6.24: Reduction of zinc oxide by carbon.

Again, in this reaction, the two processes occur together. The zinc oxide has been reduced by the carbon. In carrying out this reaction the carbon has itself been oxidised to carbon monoxide.

You will notice from these reactions that oxidation never takes place without simultaneous reduction. It is better to call these reactions oxidation–reduction reactions or **redox reactions**. During redox reactions there is both gain and loss of oxygen. Even in combustion reactions, the oxygen can be thought of as being reduced as it is no longer present as the free element.

KEY WORDS

redox reaction: a reaction involving both reduction and oxidation.

Oxidation numbers

Throughout this book, you will have noticed that the names of several compounds are written with Roman numerals in them, most often after the names of **transition metals**. Examples of such compounds include copper(II) sulfate, iron(III) oxide and cobalt(II) chloride. The reason for these numbers is that transition metal elements show variable charge. Iron in iron(III) oxide is present as the Fe^{3+} ion, copper in copper(II) sulfate is present as the Cu^{2+} ion, and so on. These metals can form other ions in different compounds. Iron can be found as Fe^{2+} ions; copper as Cu^{+} ions, for example. This number is known as the **oxidation number** (or oxidation state) of the element in a compound. If the oxidation number of a species increases, it is being oxidised; if it decreases, reduced.

KEY WORDS

transition metals (transition elements): elements from the central region of the Periodic Table; they are hard, strong, dense metals that form compounds that are often coloured.

oxidation number: a number given to show whether an element has been oxidised or reduced; the oxidation number of a simple ion is simply the charge on the ion.

Question

C6.10 Some chemical reactions are listed below.

A hexane + oxygen → carbon dioxide + water

B magnesium + oxygen → magnesium oxide

C calcium carbonate → calcium oxide + carbon dioxide

D magnesium + copper(II) oxide → magnesium oxide + copper

E hydrochloric acid + sodium hydroxide → sodium chloride + water

a Which of these reactions involve oxidation and reduction?

b Which of these reactions usually involve burning?

c What type of reaction has happened to the copper(II) oxide in equation **D**?

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Electron loss and gain in redox reactions

Chemists' ideas about oxidation and reduction have expanded as a wider range of reactions have been studied. Look again at the reaction between copper and oxygen:

$$\text{copper} + \text{oxygen} \xrightarrow{\text{heat}} \text{copper(II) oxide}$$

$$2Cu + O_2 \xrightarrow{\text{heat}} 2CuO$$

It is clear that copper has been oxidised, but what has been reduced? We can apply the ideas behind ionic equations to analyse the changes taking place during this reaction. It then becomes clear that:

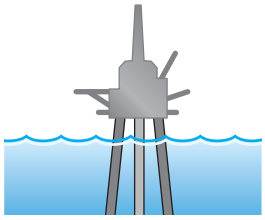
- the copper atoms in the metal have become copper ions (Cu^{2+}) in copper(II) oxide
- the oxygen molecules in the gas have split and become oxide ions (O^{2-}) in the black solid copper(II) oxide.

The copper atoms were clearly oxidised during the reaction as they have gained oxygen. We can also see that the copper atoms have lost electrons, Cu^0 has become Cu^{2+}. Note that the oxygen atoms have gained electrons in the process; O_2, where oxygen is uncharged, has become O^{2-}.

A new, broader definition of oxidation and reduction can now be put forward.

- Oxidation is the loss of electrons (an increase in oxidation number).
- Reduction is the gain of electrons (a decrease in oxidation number).

We can remember this by using the memory aid 'OIL RIG' (Figure C6.25).



OIL RIG

Oxidation **I**s the **L**oss of electrons

Reduction **I**s the **G**ain of electrons

Figure C6.25: A memory aid for remembering one definition of oxidation and reduction.

This definition of redox reactions increases the number of reactions that are classified as redox reactions. For instance, in metal **displacement reactions** where there is no transfer of oxygen, there is a transfer of electrons and hence oxidation and reduction can still be identified (Figure C6.26). Note here that the oxidation state of any uncombined element is zero.

For example, consider the metals in the following reaction (Figure C6.27a):

$$Zn(s) + CuSO_4(aq) \rightarrow ZnSO_4(aq) + Cu(s)$$

As an ionic equation this becomes (Figure C6.26):

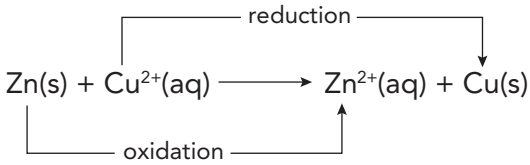


Figure C6.26: Ionic equation for the reaction between zinc and copper(II) sulfate solution.

Zinc has lost two electrons and copper has gained two electrons. This reaction is a redox reaction as there has been both loss and gain of electrons by different elements during the reaction.

Figure C6.27: Displacement reactions. **a:** reaction between zinc and copper(II) sulfate solution. **b:** Chlorine displaces iodine from potassium iodide solution.

KEY WORDS

displacement reaction: a reaction in which a more reactive element displaces a less reactive element from a solution of its salt.

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Another example of a redox reaction, is the reaction between chlorine and iodide:

$$Cl_2(aq) + 2I^-(aq) \rightarrow 2Cl^-(aq) + I_2(aq)$$

From the ionic equation we can see that the chlorine atoms of the molecule have gained electrons to become chloride ions; they have been reduced.

$$Cl_2(aq) + 2e^- \rightarrow 2Cl^-(aq) \quad \text{a reduction}$$

The iodide ions have lost electrons to form iodine; they have been oxidised. This can be observed in the formation of red-brown iodine (Figure C6.27).

$$2I^-(aq) \rightarrow I_2(aq) + 2e^- \quad \text{an oxidation}$$

As can be seen from this example, equations for redox reactions can be separated into half-equations representing the gain and loss of electrons.

ACTIVITY C6.02

Chemical crosswords

A crossword puzzle is a popular format where words are fitted together to create a grid, such as this one, based on chemical elements:

Across

3 This element has the symbol C (6 letters)

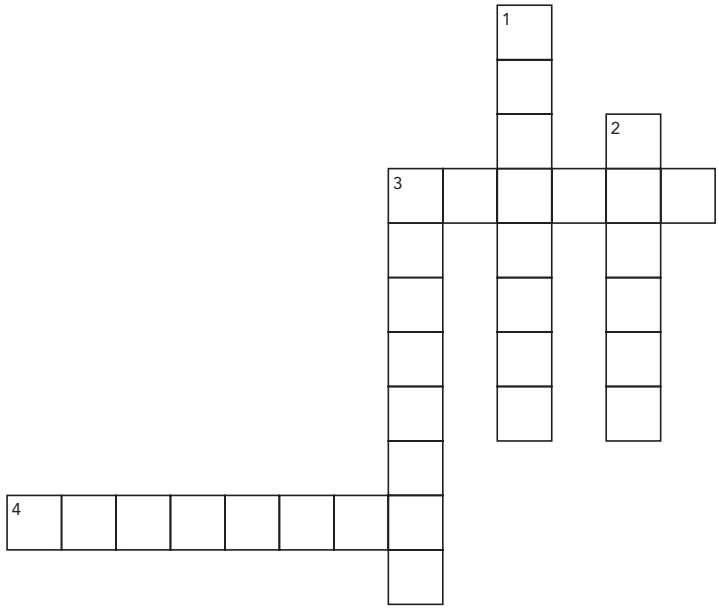
4 This is the first element on the Periodic Table (8 letters)

Down

1 This element makes up almost 88% of the atmosphere (8 letters)

2 Has the symbol Na (6 letters)

3 A toxic green gas found in Group VII (8 letters)



Your task

Create a crossword puzzle based on redox reactions.

1 Find a minimum of ten important words or short phrases in this chapter. You should be creative, e.g. 'reducing agent' could be as a single line of 13 boxes with the clue stating '(8,5 letters)' or could be split across two areas of the crossword as '1 down (8letters)' and '4 across (5 letters)'.

2 Write down the clues. These could be definitions or sentences that include a blank space for each word/phrase you have chosen.

3 Assemble a 'criss-cross' grid to fit your words/phrases. You could use various online puzzle maker apps to help you do this.

When you have completed your puzzle, challenge your partner to a race. The winner is the person to complete the other person's puzzle the quickest.

Peer assessment

When completing your partner's criss-cross puzzle, did you know all the definitions or clues? Which words did you find the easiest? Which words or clues did you find the most difficult?

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PROJECT C6.01 MODELLING CONCENTRATION

This chapter has looked at the factors that affect the rates of reaction (Figure C6.28). Working in small groups, create a visual tool or model that would help to teach someone else how concentration can affect the rate of reaction. You could use a cardboard box or some type of carton (possibly transparent), and some polystyrene spheres (or other similar materials – marbles for instance) to help you make this.

Think about the following:

- how to use one type of sphere to represent different concentrations
- how you would produce movement of the spheres
- how you would represent different reactant molecules and the process of reacting.

Present your visual tool/model to the class and explain your ideas.

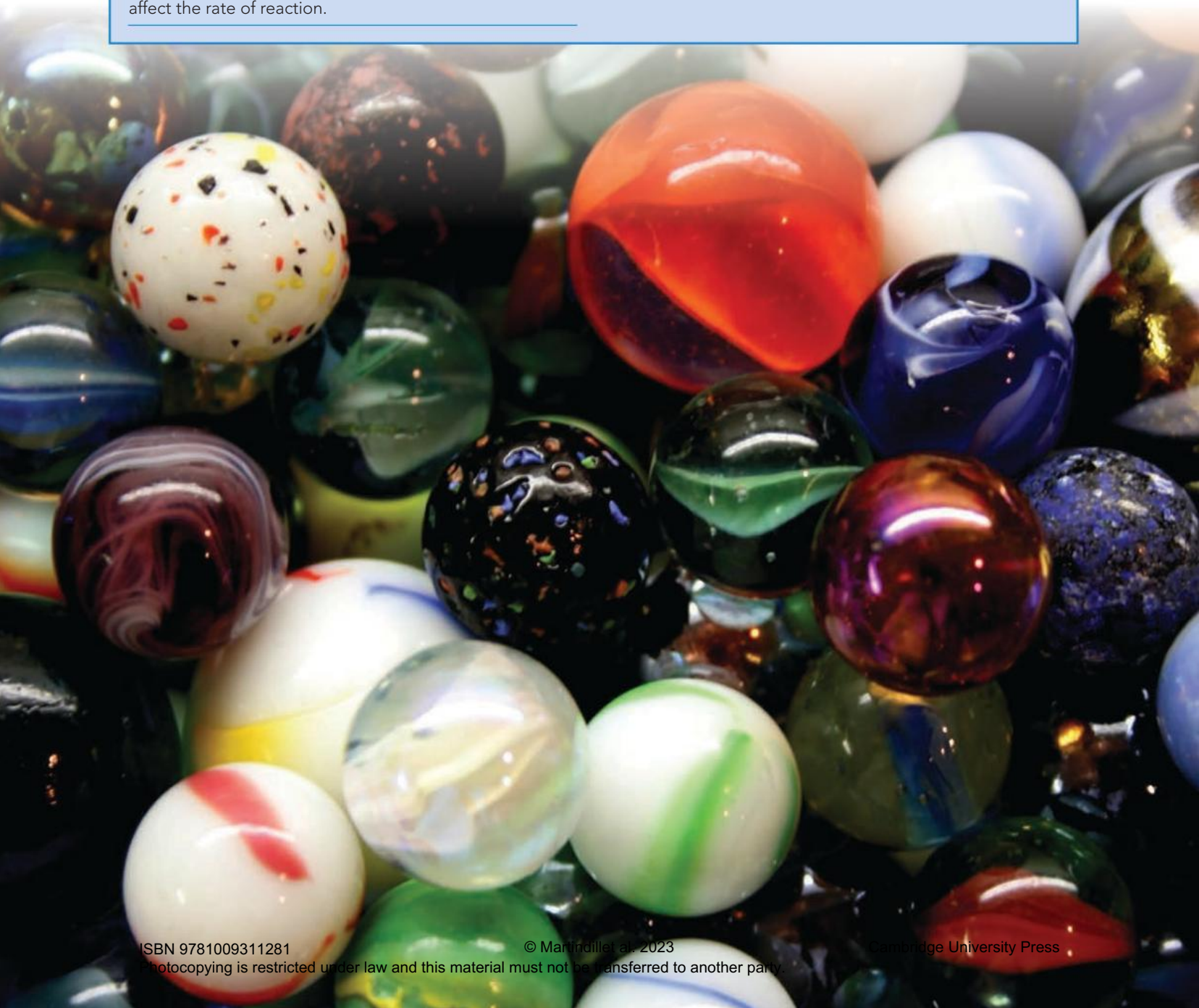

Figure C6.28: Marbles can be used to model how the concentration of the particles in a reacting mixture will affect the rate of reaction.

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SUMMARY

Physical changes are changes in the physical properties, state or situation of a substance that do not involve a change in the chemical substance(s) present. Chemical changes are changes in which a new substance is formed.
Factors such as reactant concentration, the surface area of solids, temperature and the presence of a catalyst will affect the rate of a reaction.
A catalyst increases the rate of a reaction and is unchanged at the end of that reaction.
Catalysts work by decreasing the activation energy for a reaction.
The rates of various different reactions can be investigated by suitable practical methods. The results and graphs plotted afterwards show particular patterns and give information about rate of reaction.
We can explain the effect of a range of factors by considering how the particles collide with each other.
Combustion reactions, such as the burning of natural gas, involve oxidation and reduction reactions.
Oxidation can be defined as the gain of oxygen by an element or compound during a chemical reaction. Similarly, reduction can be defined as the loss of oxygen.
Roman numerals can be used to show the oxidation number of a transition metal within a compound.
Redox reactions involve simultaneous oxidation and reduction.
Oxidation can be defined as the loss of electrons, or increase in oxidation number, during a reaction. Reduction can be defined as the gain of electrons, or decrease in oxidation number, during a reaction.

PRACTICE QUESTIONS

1 Various factors affect the rate of a chemical reaction. One of these is the surface area of a solid that is available to react when in contact with a liquid. A chemical reaction between pieces of a solid and an acid is very fast.

Identify which changes in the table would make the reaction slower.

	Acid	Pieces of solid
A	more concentrated	larger
B	less concentrated	larger
C	less concentrated	smaller
D	more concentrated	smaller

[1]

COMMAND WORD

identify: name/select/recognise.

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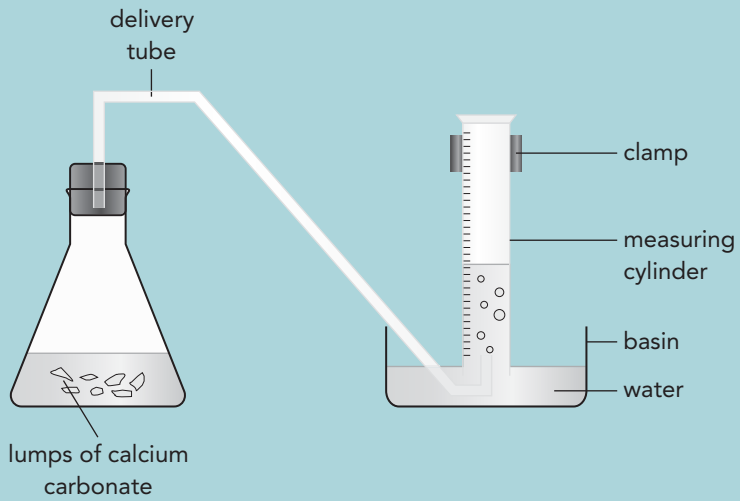
2 The rate of the reaction between lumps of calcium carbonate and dilute hydrochloric acid was investigated by collecting the gas produced, as shown in the figure.



The results obtained are given in the table.

Time / s	0	30	60	90	120	150
Volume / cm^3	10	50	70	80	90	90

a **Suggest** why the volumes at 120 and 150 seconds are the same. **[1]**

b The rate for the first 30 seconds is $\frac{40}{30} = 1.33\,cm^3/s$. **Calculate** the rate for the second 30 seconds. **[2]**

c Suggest an alternative piece of apparatus that could be used to measure the volume of gas. **[1]**

d **Give** *two* changes that could be made to the conditions that would speed up the reaction. **[2]**

[Total: 6]

3 The reaction between sodium thiosulfate and hydrochloric acid produces a finely divided precipitate of sulfur. This precipitate remains in suspension and eventually masks a cross written on a piece of paper placed below the reaction (as shown in the figure).

$$Na_2S_2O_3(aq) + 2HCl(aq) \rightarrow 2NaCl(aq) + S(s) + SO_2(g) + H_2O(l)$$

The rate of this reaction was investigated using the following experiment. A beaker containing $50\,cm^3$ of sodium thiosulfate solution was placed on a black cross. $5.0\,cm^3$ of dilute hydrochloric acid was added and the clock was started. Initially the cross was clearly visible. When the solution became cloudy and the cross could no longer be seen, the clock was stopped and the time recorded.

COMMAND WORDS

suggest: apply knowledge and understanding to situations where there is a range of valid responses in order to make proposals/put forward considerations.

calculate: work out from given facts, figures or information.

give: produce an answer from a given source or recall/memory.

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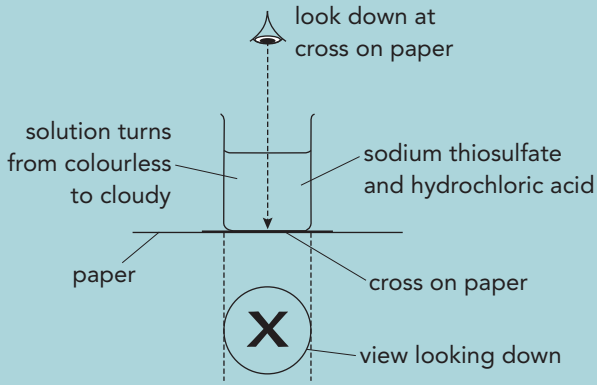

The experiment was repeated several times at different temperatures and the results are given in the table. The reaction rate is represented by $\frac{1}{\text{time}}$.

Temperature / °C	Time to obscure cross / s	$\frac{1}{\text{time}}$
20	47	0.021
30	23	0.043
40	12	0.083
50	6	0.167

a Use the information in the table to **describe** how the reaction rate varies with temperature. **[2]**

b Use ideas about reacting particles to **explain** why reaction rate changes with temperature. **[3]**

[Total: 5]

4 Zinc reacts with dilute sulfuric acid to form hydrogen.

$$Zn + H_2SO_4 \rightarrow ZnSO_4 + H_2$$

If lumps of zinc are used, the reaction is quite slow, but small pieces of zinc react more rapidly.

a **State** why smaller pieces of zinc react more rapidly. **[1]**

b If the acid is heated, the reaction takes place more rapidly. Explain why the reaction speeds up when the acid is heated. Use ideas about collisions and energy. **[2]**

[Total: 3]

COMMAND WORDS

describe: state the points of a topic/give characteristics and main features.

explain: set out purposes or reasons/make the relationships between things clear/say why and/or how and support with relevant evidence.

state: express in clear terms.

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CONTINUED

5 The equations for four different chemical reactions are listed here:

A $\underline{CaCO_3} \rightarrow CaO + CO_2$

B $\underline{Fe_2O_3} + 3CO \rightarrow 2Fe + 3CO_2$

C $\underline{CH_4} + 2O_2 \rightarrow CO_2 + 2H_2O$

D $\underline{Ca(OH)_2} + H_2SO_4 \rightarrow CaSO_4 + 2H_2O$

State the reaction in which the underlined substance is:

a oxidised **[1]**

b reduced. **[1]**

[Total: 2]

6 The equations for six different chemical reactions are listed here:

A $2CaO + C \rightarrow Ca + CO_2$

B $2KBr + Cl_2 \rightarrow 2KCl + Br_2$

C $2CuI \rightarrow Cu + CuI_2$

D $2Mg + O_2 \rightarrow 2MgO$

Use these reactions to answer the questions that follow. Each alternative may be used once, more than once, or not at all.

State which reaction:

a shows a metal being oxidised **[1]**

b shows a non-metal being oxidised **[1]**

c shows a substance being both reduced and oxidised **[1]**

d shows a non-metal being reduced. **[1]**

[Total: 4]

SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
identify physical and chemical changes and understand the differences between them	C6.01			
describe the effects of factors such as reactant concentration, the surface area of solids, temperature and the presence of a catalyst on the rate of a reaction	C6.02			
understand that a catalyst increases the rate of a reaction but remains unchanged at the end of the reaction	C6.02			
state that a catalyst decreases the activation energy of a reaction	C6.02			

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CONTINUED

I can	See topic . . .	Needs more work	Almost there	Confident to move on
investigate the rates of various different reactions and interpret the results obtained	C6.02			
describe collision theory and use it to explain how a variety of factors affect rate of reaction	C6.02			
explain how increased temperature produces an increase in reaction rate in terms of collisions	C6.02			
state that combustion reactions such as the burning of natural gas involve oxidation and reduction reactions	C6.03			
define oxidation as the gain of oxygen by an element or compound and reduction as the loss of oxygen by a compound	C6.03			
define redox reactions as involving simultaneous oxidation and reduction, and identify the gain or loss of oxygen during a reaction	C6.03			
use Roman numerals to show the oxidation number of a transition metal within a compound	C6.03			
understand that oxidation is the loss of electrons in a reaction and reduction is the gain of electrons in a reaction.	C6.03			

ISBN 9781009311281

C7 Acids, bases and salts

All learners study some content in this chapter

IN THIS CHAPTER YOU WILL:

- describe acids and bases in terms of their effect on indicators
- describe the characteristic reactions of acids
- compare the relative acidity or alkalinity or pH of a solution using universal indicator
- describe how acids and alkalis react together in neutralisation reactions
- learn that all metal oxides and hydroxides can act as bases, while many oxides of non-metals can be classified as acidic oxides
- learn that some metal oxides (amphoteric oxides) can react with both acids and alkalis
- understand that salts are an important group of ionic compounds
- learn that some salts are soluble in water, while others are insoluble
- describe the preparation, separation and purification of soluble salts by reaction of the parent acid with either excess metal, excess insoluble base or excess insoluble carbonate
- describe the preparation, separation and purification of a soluble salt by titration of an acid with an alkali
- describe the preparation of an insoluble salt by precipitation
- describe a hydrated substance as a substance that is chemically combined with water and an anhydrous substance as a substance containing no water.

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BEFORE YOU START

On a visit to a local grocery store or supermarket you can find numerous examples of everyday items that involve acids or alkalis. Get together in groups and draw up a list of such items and divide them into the two categories: acids and alkalis.

Create a table of the two categories and discuss the following questions:

1 What are the different items in your table used for?

2 How safe do you think these items are?

SCIENCE IN CONTEXT C7.01

The significance of language

Chemistry was a field of study in ancient Egypt and classical Greece. The name *kimia* came into use in these cultures and Arabic-speaking scientists modified this to *al-Kimya*. The first ideas on acidity were put forward by the Ancient Greeks and Egyptians when they defined sour tasting substances as acids. The Greeks and the Egyptians had both discovered that one substance particularly was very sour. This sour substance was produced following the fermentation of fruits and the subsequent air oxidation of the product formed. This substance became known as *vinegar* (a solution of *ethanoic acid*). Consequently, there developed a new category of substances, termed *acids*, that included all things that were sour, or sharp tasting, including lemon juice. The Latin word *acidus* means sour. The 8th-century Islamic scholar, Jabir ibn-Hayyan, is often described as the 'father of chemistry' and he is credited with the discovery of the three strong acids: sulfuric, hydrochloric and nitric acids.

The Greeks developed things further by identifying three slippery substances left behind as residue after certain materials were burnt. Potash, from burning wood, and lime, from burning seashells, were among these substances. A new terminology grew up based on these physical observations about substances. The term *alkali* was derived from the Arabic word *al-qali*, meaning 'the ashes', and was used to talk about substances that felt slippery, or soapy, to the touch. A major industry of soap making grew out of some of the substances made using alkalis.

Indeed, soap making has a long pre-industrial history and the processes involved have been exploited in different parts of the world. Black soap is a handmade soap from natural raw materials that has been used for centuries throughout Western Africa (Figure C7.01).

Figure C7.01: Making black soap in a Nigerian village.

The soap making process uses unrefined shea butter, local coconut oil or palm oil. These oils and fats are heated with the ashes of native African plant materials (e.g. plantain leaves and cocoa pods). The ashes are alkaline and act as a source of potassium hydroxide. Acid–base theory has a long and multicultural history, and its vocabulary has been influenced by the languages used by the scientists involved.

Discussion questions

1 Can you think of other words in science and mathematics that have an Arabic origin? Was there a 'golden era' of Arabic and Islamic science when such words were introduced?

2 Making soap involves using strong alkali. Why is it important that excess alkali is removed before the soap is used? What pH are most soaps you can buy?

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C7.01 The characteristic properties of acids and bases

What is an acid?

Vinegar, lemon juice, grapefruit juice and spoilt milk are all sour tasting because of the presence of **acids** (Figure C7.02). Carbonic acid from carbon dioxide dissolved in water is present in soft fizzy drinks. The acids present in these circumstances are weak and dilute. But taste is not a test that should be tried. Some acids would be dangerous, even deadly, to taste!

Figure C7.02: Citrus fruits have an 'acidic' sharp taste.

A number of acids are also **corrosive**. They can eat their way through clothing, are dangerous on the skin, and some are able to attack stonework and metals. Table C7.01 shows how common acids occur.

Indicators

The easiest way to detect whether a solution is acidic or not is to use an **indicator**. Indicators are substances that change colour if they are put into an acid or alkaline solution. Three commonly used indicators are **litmus**, **methyl orange** and **universal indicator**.

Litmus and methyl orange

Litmus is extracted from lichens and is purple in neutral solution. When it is added to an acidic solution, litmus turns red. This colour change is the result of a chemical reaction. Substances with the opposite chemical effect to acids are needed to reverse the change, and these are called **bases**. Bases turn litmus solution blue.

You can also use litmus paper. This is paper that has been soaked in litmus solution. It is available in blue and red forms.

KEY WORDS

acid: a solution of an acid turns litmus red and has a pH below 7.

corrosive: a corrosive substance (e.g. an acid) is one that can dissolve or 'eat away' at other materials (e.g. wood, metals or human skin).

indicator: a substance that changes colour when added to acidic or alkaline solutions, e.g. litmus or phenolphthalein.

litmus: the most common indicator; turns red in acid and blue in alkali.

methyl orange: an indicator which is red in acid and yellow in alkali.

universal indicator: a mixture of indicators that has different colours in solutions of different pH.

base: a substance that neutralises an acid, producing a salt and water as the only products.

Type	Name	Formula	Strong or weak?	Where found or used
Organic acids	ethanoic acid	CH_3COOH	weak	in vinegar
	methanoic acid	$HCOOH$	weak	in ant and nettle stings; used in kettle descaler
	lactic acid	$CH_3CH(OH)CO_2H$	weak	in sour milk
	citric acid	$C_6H_8O_7$	weak	in lemons, oranges and other citrus fruits
Mineral acids	carbonic acid	H_2CO_3	weak	in fizzy soft drinks
	hydrochloric acid	HCl	strong	used in cleaning metal surfaces; found as the dilute acid in the stomach
	nitric acid	HNO_3	strong	used in making fertilisers and explosives
	sulfuric acid	H_2SO_4	strong	in car batteries; used in making fertilisers, paints and detergents
	phosphoric acid	H_3PO_4	strong	in anti-rust paint; used in making fertilisers

Table C7.01: Some common acids.

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The blue form of litmus paper changes colour to red when dipped into acid solutions. Red litmus paper turns blue in alkaline solutions. **Alkalis** are **soluble** bases. Note that litmus only gives a single colour change.

Figure C7.03 shows a simple visual memory aid to help you to remember the colour change that litmus shows for acids and bases.

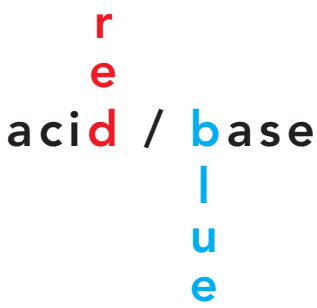

Figure C7.03: The colour change of litmus in acid (red) and base (blue).

KEY WORDS

alkali: a soluble base; a solution of an alkali turns litmus blue and has a pH above 7.

soluble: a solute that dissolves in a particular solvent.

The presence of water is very important in the action of acids and bases. One practical consequence of this is that, when we use litmus paper to test gases, it must always be damp. The gas needs to dissolve in the moisture to bring about the colour change. This is important in your practical work.

Another frequently used indicator is methyl orange. This gives a different colour change from litmus (Table C7.02) and the colour changes are sometimes easier to detect than for litmus.

Indicator	Colour in acid	Neutral colour	Colour in alkali
litmus	red	purple	blue
methyl orange	red	orange	yellow

Table C7.02: Some common indicator colour changes.

Universal indicator

Another commonly used indicator is universal indicator (or full-range indicator). It is a mixture of indicator dyes. Such an indicator is useful because it gives a range of colours (a 'spectrum') depending on the relative strength of the acid or alkali added (Figure C7.04). When you use universal indicator paper, you see that solutions of different acids produce different colours depending on their relative acidity. Solutions of the same acid with different concentrations will also give different colours.

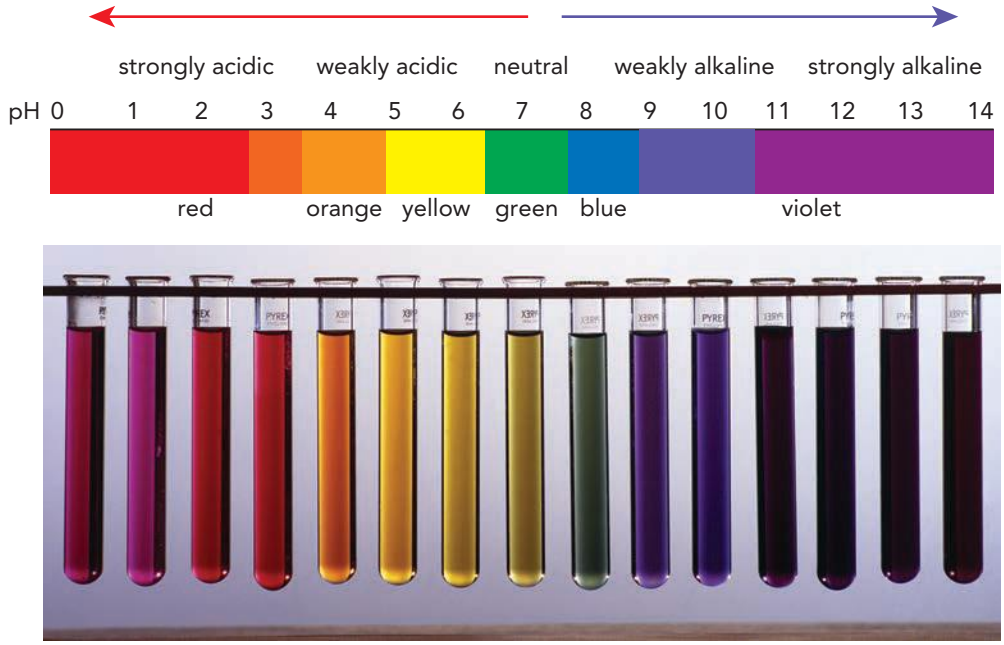

Figure C7.04: How the colour of universal indicator changes in solutions of different pH values.

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The more acidic solutions (e.g. battery acid) turn universal indicator bright red. A less acidic solution (e.g. vinegar) will only turn universal indicator orange–yellow. There are also colour differences produced with different alkali solutions. The most alkaline solutions give a violet colour.

The pH scale

The most useful measure of the relative strength of an acid or alkaline solution is the **pH scale**. The scale runs from 1 to 14 (Figure C7.04), and the following general rules apply:

- Acids have a pH less than 7; the more acidic a solution, the lower the pH.
- Neutral substances, such as pure water, have a pH of 7.
- Bases have a pH greater than 7; the more basic a solution the higher the pH.

The pH of a solution can be measured in several ways including using universal indicator or a pH meter.

It is very important to remember that the 'reference point' when measuring pH is neutrality, pH 7 – the mid-point of the scale. Therefore:

- As we move down from pH 7, the solution is getting more acidic.
- Moving up from pH 7, the solution is getting more alkaline (Table C7.03).

	Substance	pH
strongly acidic	hydrochloric acid (HCl)	0.0
↑	gastric juices	1.0
	lemon juice	2.5
	vinegar	3.0
	acid rain	4.4
	rainwater	5.6
↓	urine	6.0
weakly acidic	milk	6.5
NEUTRAL	pure water, sugar solution	7.0
weakly alkaline	blood	7.4
↑	baking soda solution	7.5
	toothpaste	9.0
	limewater	12.4
↓	household ammonia	13.0
strongly alkaline	sodium hydroxide (NaOH)	14.0

Table C7.03: The pH values of some common solutions.

Questions

C7.01 **a** What do you understand by the word corrosive?

b What acid is present in orange or lemon juice?

c What acid is present in vinegar?

C7.02 **a** Methyl orange is an indicator. What does this mean?

b Is a solution acidic, alkaline or neutral if its pH is:

i 11?

ii 7?

iii 8?

iv 3?

C7.03 Which solution is more acidic: an acid with a pH of 4 or an acid with a pH of 1?

Bases and neutralisation

When investigated, it was found that all metal oxides and hydroxides would neutralise acids. These substances are known as bases. These bases all react in the same way with acids. A base will neutralise an acid, and in the process a **salt** is formed. This type of reaction is known as a **neutralisation** reaction. It can be summed up in a general equation:

$$\text{acid} + \text{base} \rightarrow \text{salt} + \text{water}$$

Most bases are **insoluble** in water. This makes the few bases that do dissolve in water more significant. They are given a special name: alkalis. The common alkalis are shown in Table C7.04.

KEY WORDS

pH scale: a scale running from 0 to 14, used for expressing the acidity or alkalinity of a solution; a neutral solution has a pH of 7.

salt: ionic compound made by the neutralisation of an acid with a base (or alkali), e.g. copper(II) sulfate and potassium nitrate.

neutralisation: a chemical reaction between an acid and a base to produce a salt and water only.

insoluble: a substance that does not dissolve in a particular solvent.

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Name	Formula	Strong or weak?	Where found or used
sodium hydroxide (caustic soda)	NaOH	strong	in oven cleaners (degreasing agent); in making soap and paper; other industrial uses
potassium hydroxide (caustic potash)	KOH	strong	in making soft soaps and biodiesel
calcium hydroxide (limewater)	$Ca(OH)_2$	strong	to neutralise soil acidity and acidic gases produced by power stations; has limited solubility
ammonia solution (ammonium hydroxide)	$NH_3(aq)$ or NH_4OH	weak	in cleaning fluids in the home (degreasing agent); in making fertilisers
calcium oxide	CaO	—	for neutralising soil acidity and industrial waste; in making cement and concrete
magnesium oxide	MgO	—	in antacid indigestion tablets

Table C7.04: Some common alkalis and bases.

An example of a neutralisation reaction is:

hydrochloric acid + sodium hydroxide → sodium chloride + water

$HCl(aq) + NaOH(aq) \rightarrow NaCl(aq) + H_2O(l)$

All these compounds are completely ionised, except for the water produced. The hydrogen ions from the acid and the hydroxide ions from the alkali have combined to form water molecules. We can show this in the following equation:

$H^+(aq) + OH^-(aq) \rightarrow H_2O(l)$

hydrogen ions + hydroxide ions → water

This is the ionic equation for this neutralisation reaction. The spectator ions (chloride and sodium ions) remain in solution, which becomes a solution of sodium chloride (Figure C7.05).

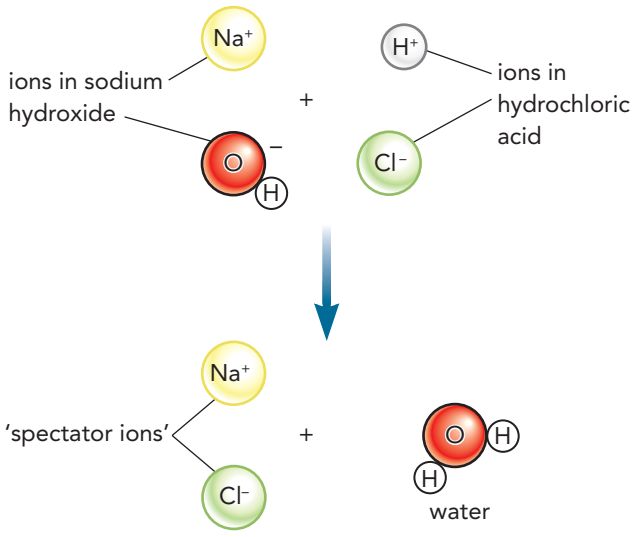

Figure C7.05: Reactions of ions when hydrochloric acid is mixed with sodium hydroxide.

By evaporating some of the water, the salt can be crystallised out. In fact, the same ionic equation can be used for any reaction between an acid and an alkali.

Characteristic reactions of acids

There are three major chemical reactions in which all acids will take part. These reactions are best seen using dilute acid solutions. In these reactions, the acid reacts with:

- a reactive metal (e.g. magnesium or zinc: Figure C7.06)
- a base (or alkali): a neutralisation reaction
- a metal carbonate or hydrogen carbonate (Figure C7.07).

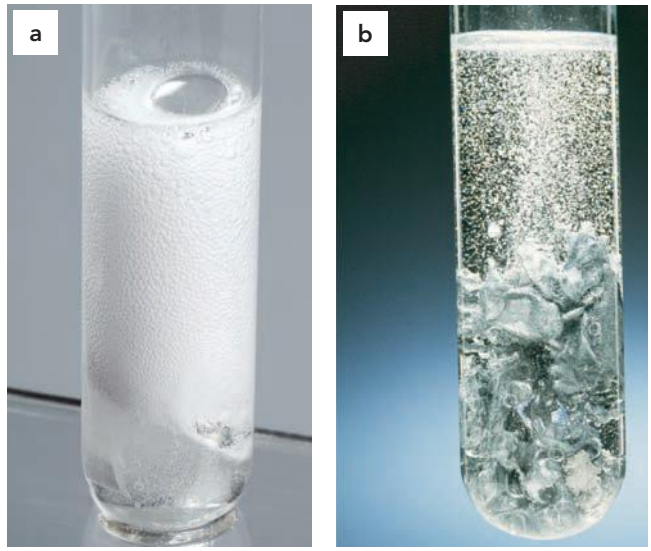

Figure C7.06 a: Magnesium ribbon. **b:** Zinc granules, reacting with hydrochloric acid and giving off hydrogen.

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Figure C7.07: Some antacid tablets are designed to fizz. They contain sodium hydrogencarbonate and citric acid, which react together in water.

One type of product is common to all these reactions. They all produce a metal compound called a salt.

Normally, we use the word 'salt' to mean 'common salt', which is sodium chloride. This is the salt we put on our food, the main salt found in seawater, and the salt used over centuries to preserve food. However, in chemistry, the word has a more general meaning. A salt is a compound made when a metal takes the place of the hydrogen in an acid. The acid from which the salt is made is often called the parent acid of the salt.

Reaction of acids with metals

Metals that are quite reactive can safely be used to displace the hydrogen from an acid. Hydrogen gas is given off. The salt made depends on the combination of metal and acid used:

metal + acid → salt + hydrogen

It is unsafe to try this reaction with very reactive metals such as sodium or calcium. The reaction is too violent. No reaction occurs with metals, such as copper, that are less reactive than lead. Even with lead, it is difficult to see any reaction in a short time. The reactivity of metals with acids is considered in more detail in Chapter C9.

The salt made depends on the acid reacted with the metal:

- Hydrochloric acid always gives a chloride.
- Nitric acid always gives a nitrate.
- Sulfuric acid always gives a sulfate.

For example:

magnesium + nitric acid → magnesium nitrate + hydrogen

$Mg(s) + 2HNO_3(aq) \rightarrow Mg(NO_3)_2(aq) + H_2(g)$

zinc + hydrochloric acid → zinc chloride + hydrogen

$Zn(s) + 2HCl(aq) \rightarrow ZnCl_2(aq) + H_2(g)$

Reaction of acids with bases

This is the neutralisation reaction that we saw earlier:

acid + base → salt + water

The salt produced by this reaction will depend on the combination of reactants used. To make a particular salt, you choose a suitable acid and base to give a solution of the salt you want. Examples of salts made from different combinations of acid and base are shown in Table C7.05.

	Salt made with . . .		
Base	Hydrochloric acid (HCl)	Nitric acid (HNO_3)	Sulfuric acid (H_2SO_4)
sodium hydroxide (NaOH)	sodium chloride, NaCl	sodium nitrate, $NaNO_3$	sodium sulfate, Na_2SO_4
potassium hydroxide (KOH)	potassium chloride, KCl	potassium nitrate, KNO_3	potassium sulfate, K_2SO_4
magnesium oxide (MgO)	magnesium chloride, $MgCl_2$	magnesium nitrate, $Mg(NO_3)_2$	magnesium sulfate, $MgSO_4$
copper oxide (CuO)	copper chloride, $CuCl_2$	copper nitrate, $Cu(NO_3)_2$	copper sulfate, $CuSO_4$

Table C7.05: Some examples of making salts using alkalis or insoluble bases.

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It is useful to realise the origins of a salt because it helps you predict which salt is produced from a particular combination of acid and base.

Reaction of acids with carbonates

All carbonates give off carbon dioxide when they react with acids (Figure C7.08). We have seen that this reaction occurs with effervescent antacid tablets. The result is to neutralise the acid and produce a salt solution:

acid + metal carbonate → salt + water + carbon dioxide

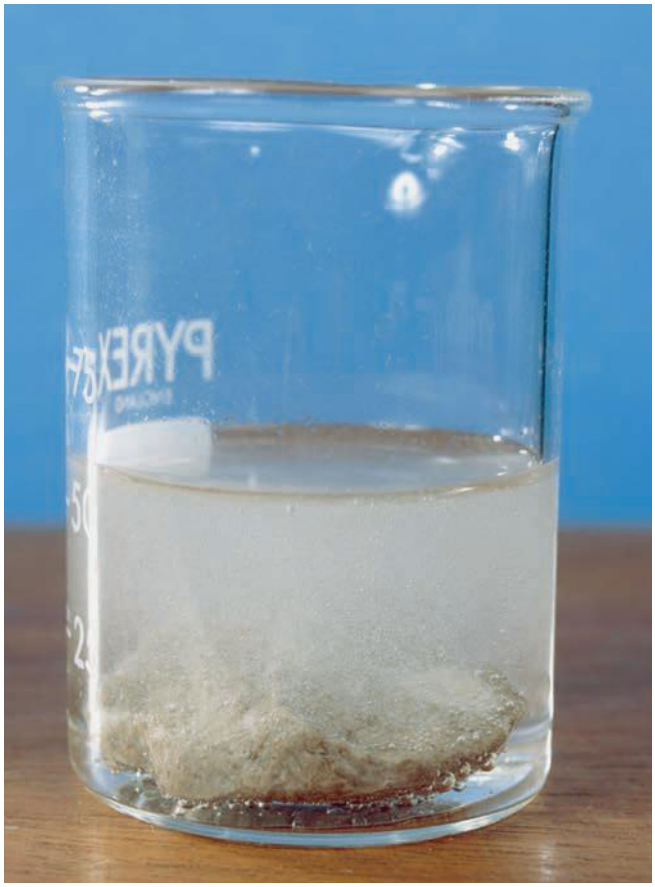

Figure C7.08: Limestone (calcium carbonate) reacting with acid.

The normal method of preparing carbon dioxide in the laboratory is based on this reaction. Dilute hydrochloric acid is reacted with marble chips (calcium carbonate):

$$\underset{\text{acid}}{\text{hydrochloric}} + \underset{\text{carbonate}}{\text{calcium}} \rightarrow \underset{\text{chloride}}{\text{calcium}} + \text{water} + \underset{\text{dioxide}}{\text{carbon}}$$

$$2HCl(aq) + CaCO_3(s) \rightarrow CaCl_2(aq) + H_2O(l) + CO_2(g)$$

EXPERIMENTAL SKILLS C7.01

Comparing the effectiveness of different antacid tablets

Antacid tablets relieve the symptoms of acid indigestion by neutralising the excess acid. Many of these indigestion tablets contain insoluble carbonates or bases such as calcium carbonate, magnesium carbonate or magnesium hydroxide. This activity involves titrating powdered samples of antacid tablets with dilute hydrochloric acid.

You will need:

- a selection of antacid tablets
- dilute hydrochloric acid (0.5 mol/dm^3)
- methyl orange indicator
- burette
- burette stand
- conical flask (100 cm^3)
- spatula
- small filter funnel
- balance
- mortar and pestle.

Safety

Wear eye protection throughout. Be careful with chemicals. Never ingest them and always wash your hands after handling them.

Getting started

Familiarise yourself with the apparatus you are about to use. While washing out the burette and filling with acid make sure that you can comfortably read the burette scale. Make sure you are clear about the colour change you will observe with methyl orange indicator. It can be useful for you to set up two small beakers showing the indicator in some acid and alkali and then keep these as a reminder to you as you carry out the experiment. You may find it useful to refer to the process outlined in Method B in Figure C7.13.

Method

1. Set up a burette. Use a small filter funnel to fill the burette with the dilute hydrochloric acid solution.
2. Choose an antacid tablet and note its brand name. Weigh this tablet on the balance and record the mass of the tablet.
3. Draw up a results table in which to record your burette readings.

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CONTINUED: C7.01

4 Grind up the tablet into a powder using the mortar and pestle. Transfer all the powder to the conical flask and add a little water.

5 Add about 10 drops of methyl orange indicator and swirl the flask.

6 In your results table, record the initial reading of the burette.

7 Perform the **titration** by adding the acid from the **burette**. Keep swirling the flask as you do so. Allow time for the acid to react with the powder. The colour of the solution will flash red and will get stronger as you add more acid. When you are close to the **end-point**, add the acid one drop at a time. When the solution stays permanently red after swirling, do not add any more acid.

8 In your results table, record the final reading of the burette.

Questions

1 Which brand of tablet did you judge to be the most effective in neutralising acid indigestion? Comment on the criteria you used to make this judgement.

2 Examine the packaging of the tablets. Write word equations for the reaction between the active ingredient in each case and the hydrochloric acid. Write the balanced chemical equation for the reaction of at least one of the tablets.

3 Why were the tablets crushed before carrying out the reaction?

Peer assessment

Titrations require precise and accurate use of specific equipment and careful reading of the values obtained. Do you understand how to construct a results table to record your data? Discuss with your partner the reliability of the readings you took and your organisation of the work involved. What areas do you think you could improve?

KEY WORDS

titration: a method of quantitative analysis using solutions: one solution is slowly added to a known volume of another solution using a burette until an end-point is reached.

burette: a piece of glass apparatus used for delivering a variable volume of liquid accurately.

end-point: the point in a titration when the indicator just changes colour, showing that the reaction is complete.

Questions

C7.04 What is the formula for:

a sulfuric acid?

b hydrochloric acid?

C7.05 **a** Write the balanced symbol equations for the reaction between:

i copper oxide and nitric acid

ii zinc and hydrochloric acid.

b The ionic equation for the reaction in **ii** is:

$Zn(s) + 2H^+(aq) \rightarrow Zn^{2+}(aq) + H_2(g)$

Explain why this can be regarded as a redox reaction. State which reactant has been oxidised.

C7.02 Oxides

Acidic and basic oxides

Venus, our nearest neighbour in the solar system, is identical in size and density to the Earth. But Venus has yielded its secrets reluctantly because it is veiled in clouds and has an atmosphere that is very damaging to space probes. The *Venus Express* spacecraft (Figure C7.09) launched by the European Space Agency conducted the most comprehensive study of the thick atmosphere responsible for the intense greenhouse effect on the planet.

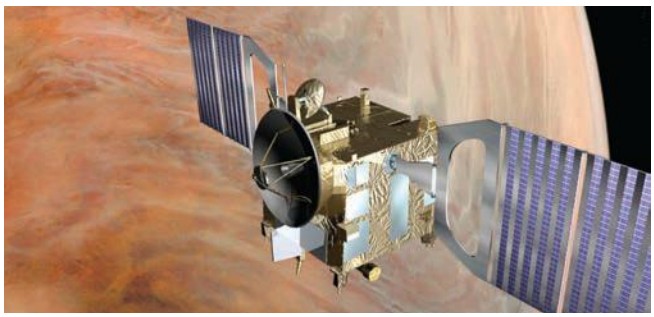

Figure C7.09: Image of the Venus Express probe orbiting above the clouds of Venus's atmosphere.

The sulfuric acid clouds of Venus are the product of great volcanic activity. This has thrown out huge amounts of water vapour and the oxides of sulfur into the planet's atmosphere. Similar acidic clouds can be made in a gas jar by lowering burning sulfur into oxygen (Figure C7.10).

$$2S(s) + O_2(g) \rightarrow 2SO\ (g)$$

Other burning non-metals (e.g. carbon) react in the same way to produce acidic gases.

$$C(s) + O_2(g) \rightarrow CO_2(g)$$

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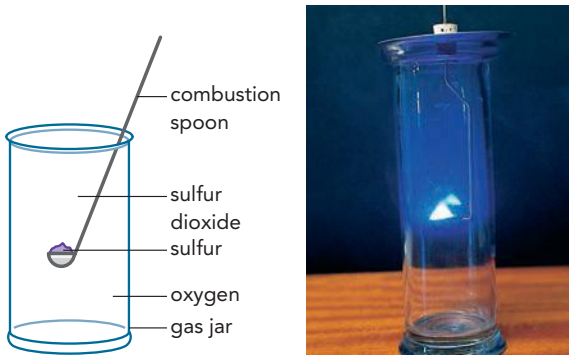

Figure C7.10: Burning sulfur in a gas jar of oxygen.

When water is added to the gas jars, it dissolves the gases and gives solutions that turn blue litmus paper red. Turning litmus paper red shows that these solutions contain acids. These solutions are the product of burning non-metals to produce **acidic oxides**.

Burning metals produces oxides that, if they dissolve, give solutions that turn litmus paper blue. The metal oxides produced in these reactions react with acids to neutralise them. They are said to be **basic oxides** (Table C7.06).

KEY WORDS

acidic oxide: oxide of a non-metal that will react with bases and dissolve in water to produce an acid solution.

basic oxide: oxide of a metal that will react with acids to neutralise the acid.

ACTIVITY C7.01

The environmental impact of acidic oxides

Acid rain can have a devastating effect on trees. Rain is normally slightly acidic, with a pH of 5.6, while acid rain generally has a pH between 4.2 and 4.4. Fossil fuels are contaminated with the non-metal, sulfur. When the fuels are burnt, the sulfur is converted into the gaseous acidic oxide, sulfur dioxide (SO_2). Fossil-fuel powered vehicles also produce acidic oxides of nitrogen (NO and NO_2, sometimes referred to as NO_x), which are released into the atmosphere.

Once released, the pollutant gases react with water, oxygen and other chemicals in the atmosphere to form acidic compounds such as sulfuric and nitric acids. The problem of acid rain is not confined to the geographical location in which it forms, however. This pollution can be carried by prevailing winds through the atmosphere for hundreds of kilometres. Once acid rain falls, it sinks into the soil and also enters the water system through surface runoff. (For further discussion of acid rain see Chapter C10.)

In groups, create an educational flyer on the origins and consequences of acid rain for distribution at a student environmental conference. Your flyer should include text and artwork and could cover some of the following topics (though not necessarily all):

- the origins of acid rain (acid deposition) including an equation for the production of one of the acids mentioned
- the nature of the pH scale – its direction and the meaning of one division on the scale

Element	How it reacts	Product	Effect of adding water and testing with litmus
Non-metals			
sulfur	burns with bright blue flame	colourless gas (sulfur dioxide, SO_2)	dissolves, turns litmus red
phosphorus	burns with yellow flame	white solid (phosphorus(V) oxide, P_2O_5)	dissolves, turns litmus red
carbon	glows red	colourless gas (carbon dioxide, CO_2)	dissolves slightly, slowly turns litmus red
Metals			
sodium	burns with yellow flame	white solid (sodium oxide, Na_2O)	dissolves, turns litmus blue
magnesium	burns with bright white flame	white solid (magnesium oxide, MgO)	dissolves slightly, turns litmus blue
calcium	burns with red flame	white solid (calcium oxide, CaO)	dissolves, turns litmus blue
iron	burns with yellow sparks	blue–black solid (iron oxide, FeO)	insoluble
copper	does not burn, turns black	black solid (copper oxide, CuO)	insoluble

Table C7.06: Reactions of certain elements with oxygen.

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CONTINUED

- the effects of acid rain on trees, lakes (and the life in them), and on buildings (include an equation for the effect of, say, nitric acid on limestone)
- prevention and remedy of the effects; addition of lime to acidified lakes (a neutralisation reaction), for instance.

Neutral and amphoteric oxides

Water can be thought of as hydrogen oxide. It has a pH of 7 and is therefore a neutral oxide. It is an exception to the broad 'rule' that the oxides of non-metals are acidic oxides. Neutral oxides do not react with either acids or alkalis. There are a few other exceptions to this 'rule' (Figure C7.11). The most important is the poisonous gas carbon monoxide (CO). The 'rule' that most non-metal oxides are acidic remains useful and important, however.

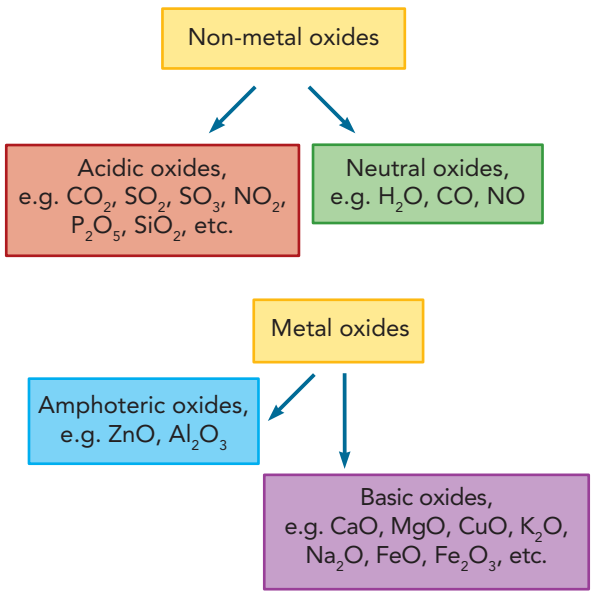

Figure C7.11: The classification of non-metal and metal oxides.

Of more importance is the unusual behaviour of some metal oxides. These metal oxides react and neutralise acids; they react as bases, which would be expected. However, they can also neutralise alkalis. In this case, they are reacting as acids, which is unusual. Metal oxides that can react as either an acid or a base to produce a salt and water are called **amphoteric compounds**.

The most important examples of metals that have amphoteric compounds are zinc and aluminium. Zinc oxide and aluminium oxide both react with acids to produce the expected salt and water. For example:

$$ZnO(s) + 2HCl(aq) \rightarrow ZnCl_2(aq) + H_2O(l)$$

However, they also react with an alkali to produce a salt and water.

acid	+	alkali	→	salt	+	water
$ZnO(s)$	+	$2NaOH(aq)$	→	$Na_2ZnO_2(aq)$	+	$H_2O(l)$
zinc oxide	+	sodium hydroxide	→	sodium zincate	+	water
$Al_2O_3(s)$	+	$2NaOH(aq)$	→	$2NaAlO_2(aq)$	+	$H_2O(l)$
aluminium oxide	+	sodium hydroxide	→	sodium aluminate	+	water

The salts formed in the reactions with sodium hydroxide are soluble and contain compound ions. Their names end in *-ate* because they contain oxygen.

Questions

C7.06 **a** What colour is the flame when sulfur burns?

b Write the symbol equation for the reaction when sulfur burns in oxygen.

c Write the word equation for magnesium burning in air.

C7.07 Define the term *amphoteric oxide*. Write the balanced symbol equations for the reactions of aluminium oxide with hydrochloric acid and sodium hydroxide.

C7.08 Name *one* amphoteric metal hydroxide and write the word and symbol equations for its reaction with sodium hydroxide solution.

C7.03 Preparation of salts

In chemistry, a salt is defined as a compound formed from an acid by the replacement of the hydrogen in the acid by a metal or by ammonium ions. Salts are ionic compounds. There is a wide range of salts.

KEY WORDS

amphoteric compound: a compound (hydroxide or metal oxide) that can react with either an acid or an alkali to give a salt and water.

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Sodium chloride, commonly known as salt, is essential for life and is an important raw material for industries. Biologically, it has a number of functions: it is involved in muscle contraction; it enables the conduction of nerve impulses in the nervous system; it regulates osmosis (the passage of solvent molecules through membranes); and it is converted into the hydrochloric acid that aids digestion in the stomach. When we sweat, we lose both water and sodium chloride. Losing too much salt during sport and exercise can give us muscle cramp. Isotonic drinks are designed to replace this loss of salt and to restore energy and the balance of mineral ions in our body.

Solubility of salts

A number of salts can be obtained by mining, but others must be made by industry. Therefore, it is worth considering the methods available to make salts. Some of these can be investigated in the laboratory.

Whether the salt is soluble or insoluble in water influences the preparation method chosen. Table C7.07 outlines the general patterns of solubility for the most common salts.

Salts	Soluble	Insoluble
sodium salts	all are soluble	none
potassium salts	all are soluble	none
ammonium salts	all are soluble	none
nitrates	all are soluble	none
chlorides	most are soluble	silver chloride, lead(II) chloride
sulfates	most are soluble	barium sulfate, lead(II) sulfate, calcium sulfate
carbonates	sodium, potassium and ammonium carbonates	most are insoluble

Table C7.07: The patterns of solubility for various types of salts.

Table C7.07 is organised to help you to remember the following points:

- All the common sodium, potassium and ammonium salts are soluble.
- All nitrates are soluble.
- Most chlorides and sulfates are soluble: the most important exceptions are silver chloride and barium sulfate, which are important precipitates in chemical analysis.
- Almost all carbonates are insoluble.

Questions

C7.09 What are the parent acids of the following salts?

- **a** potassium sulfate
- **b** silver nitrate
- **c** calcium carbonate

C7.10 Which acid and alkali would react to form the following salts?

- **a** sodium chloride
- **b** calcium nitrate
- **c** ammonium sulfate

C7.11

- **a** The salts of which acid are all soluble in water?
- **b** Which *two* of the following salts are soluble in water?

  lead chloride; potassium sulfate; barium sulfate; silver chloride; ammonium nitrate

ACTIVITY C7.02

Oceans of seawater

The Earth has been referred to as the blue planet because so much of its surface is covered by water. Only about 3% of this water is freshwater; most of it is saltwater. Saltwater is the water that is present in the seas and oceans that cover approximately 71% of the surface of the Earth.

Working in small groups, create a colourful poster on the salt composition (salinity) of the water on the surface of the Earth. Use the following information to help you.

Figure C7.12 shows data on the overall concentration of various ions in seawater.

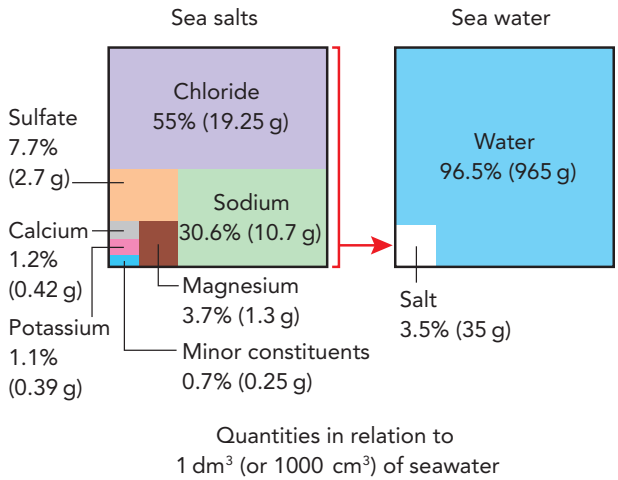

Figure C7.12: Data on the overall salt concentration of seawater.

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CONTINUED

Use the data in Figure C7.12 to suggest some of the major salts present in seawater. On your poster, make a table of these salts and suggest which acid and base or carbonate could have reacted to produce them. Relate your list to the solubilities of different types of salt (Table C7.07).

The distribution of salts in the oceans is not uniform. For example, the Red Sea has a salinity of 40%, the Mediterranean 38%, while the salinities of the Black Sea (18%) and the Baltic Sea (8%) are much lower.

- Research and comment on the factors that produce this variation in salt concentration in different regions on your poster. Does temperature influence the composition? Is the outflow from major rivers an influence?
- How would you prepare a sample of salt from a known volume of seawater to find a value for the total salt concentration in g/dm^3?
- Include this, alongside a photograph or drawing of the apparatus, on your poster.

Prepare your poster and then present and discuss it with the whole class.

Preparing soluble salts

Soluble salts can be made from their parent acid using any of the three characteristic reactions of acids outlined earlier in this chapter.

When crystallised, many salts contain water that is chemically combined in the crystal structure. Such salts are an important group of **hydrated substances**. They are known as *hydrated salts*. When preparing crystals of a hydrated salt, we must be careful not to heat them too strongly when drying them. If we do heat too strongly then the product is an **anhydrous** (dehydrated) powder, not crystals.

Choosing a method of salt preparation

The choice of method for preparing a soluble salt depends on two things:

1 Does the metal react with the acid? If it does, is it too reactive and therefore unsafe? This is covered further in Chapter C9.

2 Is the base or carbonate soluble or insoluble?

Figure C7.13 shows a flow chart summarising the choices to be made when preparing a soluble salt.

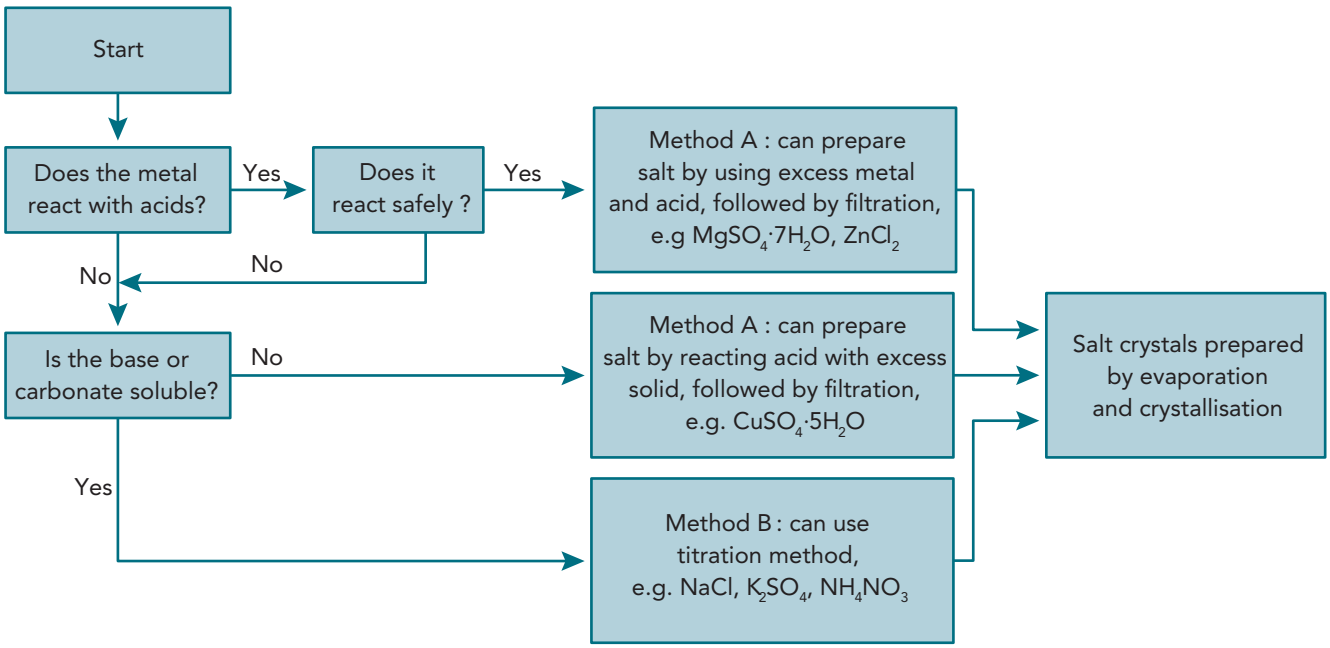

Figure C7.13: Flow chart showing which method to use for preparing soluble salts.

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KEY WORDS

hydrated substance: a substance that is chemically combined with water; *hydrated salts* are an important group of such substances.

anhydrous: an adjective to describe a substance without water combined with it.

Method A: Acid plus solid metal, base or carbonate

Method A is essentially the same whether you are starting with a solid metal, a solid base or a solid carbonate (Figure C7.14):

- **Stage 1:** An excess of the solid is added to the acid and allowed to react. Using an excess of the solid makes sure that all the acid is used up. If it is not used up at this stage, the acid would become more concentrated when the water is evaporated later (Stage 3).
- **Stage 2:** The excess solid is filtered out.
- **Stage 3:** The filtrate is gently evaporated to concentrate the salt solution. This can be done on a heated water-bath or sand tray (Figure C7.15).
- **Stage 4:** When crystals can be seen forming (crystallisation point), heating is stopped and the solution is left to crystallise.
- **Stage 5:** The concentrated solution is cooled to let the crystals form. The crystals are filtered off and washed with a little distilled water. Then the crystals are dried carefully between filter papers (Figure C7.16).

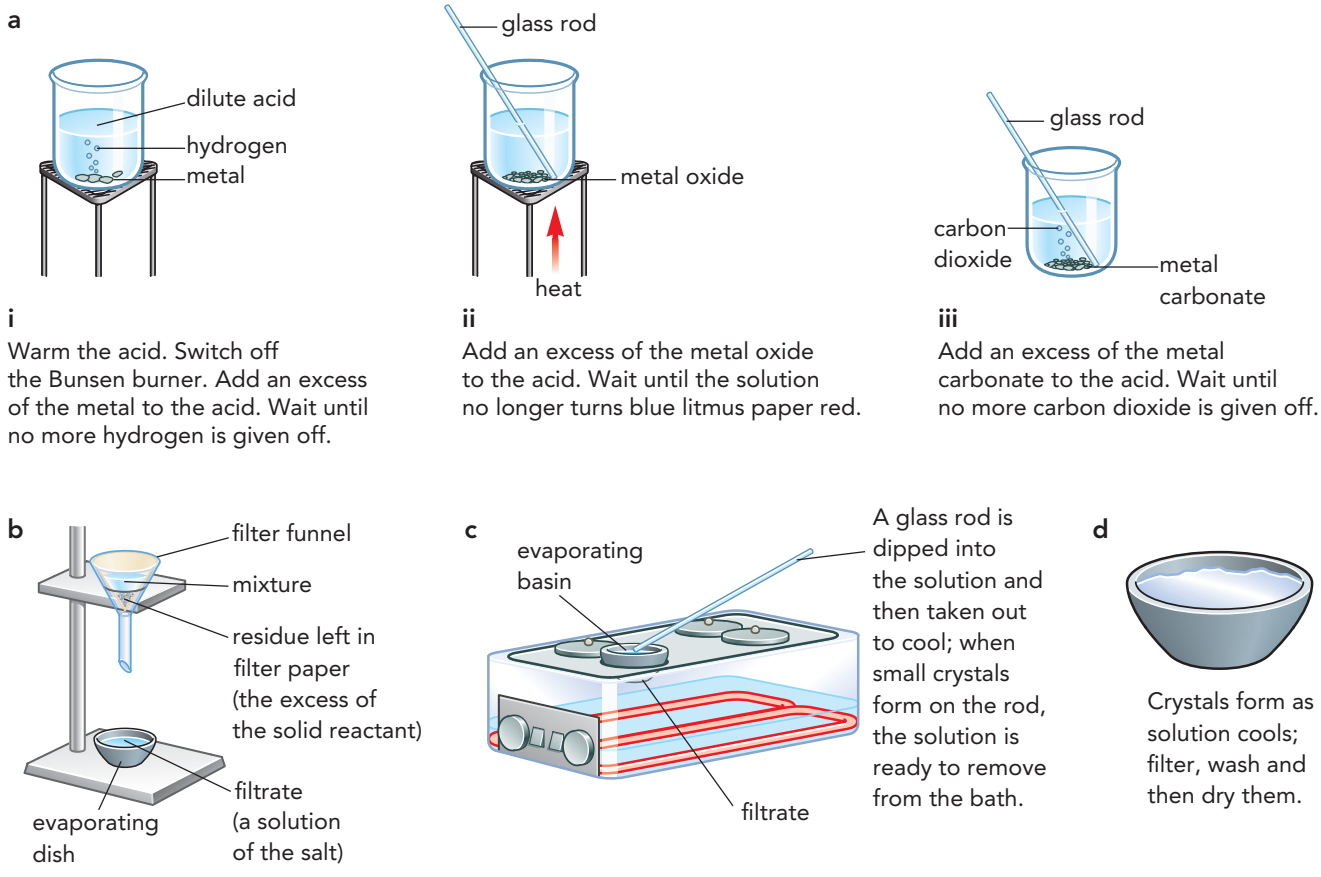

Figure C7.14: Method A for preparing a soluble salt. **a:** Stage 1: the acid is reacted with either (i) a metal, (ii) a base or (iii) a carbonate. **b:** Stage 2: the excess solid is filtered out. **c:** Stage 3: the solution is carefully evaporated. **d:** Stage 4: the crystals are allowed to form.

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Figure C7.15: Evaporating off the water to obtain salt crystals. Here a sand tray is being used to heat the solution carefully.

Figure C7.16: Crystals of zinc nitrate after drying between filter papers.

Method B: Acid plus alkali by titration

Method B (the titration method) involves the neutralisation of an acid with an alkali (e.g. sodium hydroxide) or a soluble carbonate (e.g. sodium carbonate) (Figure C7.17). Since both the reactants and the products are colourless, an indicator is used to find the neutralisation point or end-point.

- **Stage 1:** The acid solution is poured into a burette. The burette is used to accurately measure the volume of solution added. A known volume of alkali solution is placed in a conical flask using a **volumetric pipette**. The pipette delivers a fixed volume accurately.

  A few drops of an indicator (e.g. thymolphthalein or methyl orange) are added to the flask.

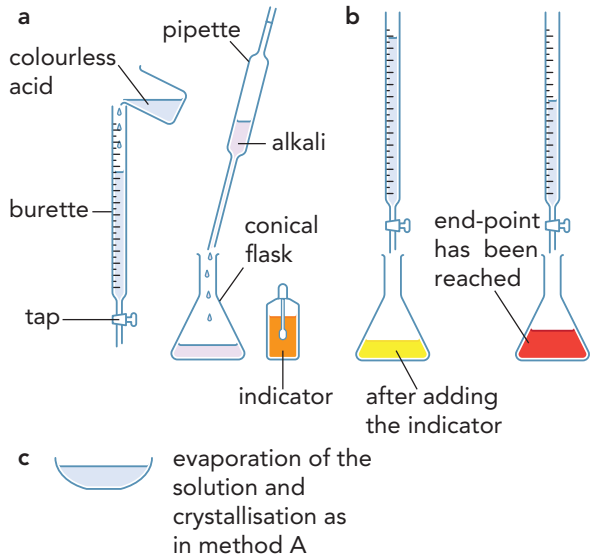

Figure C7.17: Method B (the titration method) for preparing a soluble salt. **a:** Stage 1: the burette is filled with acid and a known volume of alkali is added to the conical flask. **b:** Stage 2: the acid is added to the alkali until the end-point is reached. **c:** Stage 3: the solution is evaporated and crystallised as for method A.

- **Stage 2:** The acid solution is run into the flask a few drops at a time from the burette until the indicator just changes colour (Figure C7.18). The conical flask must also be swirled after each portion of acid to ensure everything is mixed and the reaction is complete. When the end-point for the reaction has been found, the volume of acid (titre volume) added is noted. The experiment is then repeated without using the indicator. The same known volume of alkali is used in the flask. The same volume of acid as noted in the first part is then run into the flask. Alternatively, activated charcoal can be added to remove the coloured indicator. The charcoal can then be filtered off.
- **Stage 3:** The salt solution is evaporated and cooled to form crystals as described in method A.

KEY WORDS

volumetric pipette: a pipette used to measure out a volume of solution accurately.

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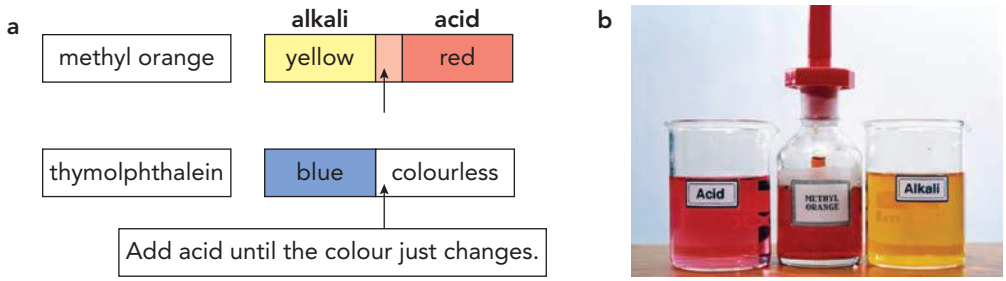

Figure C7.18 a: Colour changes for the indicators methyl orange and thymolphthalein during the titration. **b:** Actual colours of methyl orange in acid and alkali.

This titration method is very useful not only for preparing salts but also for finding the concentration of a particular acid or alkali solution (see Chapter C12).

EXPERIMENTAL SKILLS C7.02

Quick and easy copper(II) sulfate crystals

This activity is an adaptation of the larger-scale method of preparing a soluble salt (see Figure C7.14). The essential feature of this method is that it is easier to carry out than the method involving multiple stages. The method uses a reaction between a dilute solution of the parent acid (sulfuric acid in this case) and an excess of an insoluble base.

You will need:

- measuring cylinder (25 cm^3)
- boiling tube
- sulfuric acid (2 mol/dm^3)
- beaker (250 cm^3)
- copper(II) oxide
- filter funnel and filter paper
- conical flask (100 cm^3)
- crystallising dish
- Bunsen burner
- tripod and gauze
- heat-resistant mat
- kettle
- balance.

Safety

Wear eye protection throughout. Be careful with chemicals. Never ingest them and always wash your hands after handling them. Note that sulfuric acid is corrosive and an irritant at the concentration used.

Getting started

It is important that you are well organised and have all the apparatus and chemicals that you need before starting the experiment. You should be familiar with the techniques of filtration and crystallisation (Chapter C12). You may find it helpful to set up the filtration apparatus before starting.

Method

1. Pour 15 cm^3 of 2 mol/dm^3 sulfuric acid into a boiling tube.
2. Place the tube in a beaker half-filled with boiling water from a kettle.
3. Weigh out between 1.8 g and 2.0 g of copper(II) oxide.
4. Add half the copper(II) oxide to the acid in the boiling tube. Shake the boiling tube and return it to the hot water.
5. When the solid has dissolved, add the remaining portion of copper(II) oxide.
6. Keep the tube in the hot water for five more minutes, taking it out occasionally to shake the tube.
7. Filter off the unreacted solid, collecting the clear blue solution in a 100 cm^3 conical flask. A fluted filter paper can be used to speed up the filtration.
8. Set up the Bunsen burner and boil the solution for two to three minutes.
9. Pour the hot solution into a clean, dry crystallising dish and watch the crystals grow!

Questions

1. Write word and balanced chemical equations for the reaction taking place.
2. What does the fact that there is some unreacted solid left after the reaction tell you about the proportions of reactants used? Why is it useful that the reaction is carried out with these proportions?

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CONTINUED: C7.02

Peer assessment

The practical work to prepare copper(II) sulfate crystals requires careful and coordinated work with your partner. When you have completed the experiment, discuss with your partner how efficiently you worked together. Think about the following questions:

- Were you able to handle the manipulation of the reaction, filtration and crystallisation stages confidently?
- Did you share the work equally between you?
- Did carrying out the experiment help you to understand the importance of the different steps involved in preparing a soluble salt?

Reflection

Do you find carrying out practical work a useful way of learning aspects of chemistry?

Is there a way in which you could gain more from performing experiments?

Questions

C7.12 Name the salts formed when:

- **a** dilute hydrochloric acid reacts with magnesium
- **b** calcium oxide reacts with dilute nitric acid
- **c** zinc carbonate reacts with dilute sulfuric acid.

C7.13

- **a** In the methods of preparing a salt using a solid metal, base or carbonate, why is the solid used in excess?
- **b** In such methods, how is the excess solid removed once the reaction has finished?
- **c** Name the *two* important pieces of graduated glassware used in the titration method of preparing a salt.
- **d** What colour is the indicator methyl orange in alkali?
- **e** Why should the crystals prepared at the end of experiments to prepare salts not be heated too strongly when drying them?

C7.14 There are two methods of preparing soluble salts depending on the solubility of the reagent reacted with the acid: method A (titration using a burette and an indicator) and method B (addition of an excess of a base or a metal to a dilute acid and removal of the excess solid).

- **a** Which method, A or B, would you use to prepare the soluble salt, zinc sulfate, from the insoluble base, zinc oxide?
- **b** Write down the reagent to use.
- **c** Write the word equation.

Preparing insoluble salts

The reaction between marble chips (calcium carbonate) and sulfuric acid would be expected to produce a strong reaction, with large amounts of carbon dioxide being given off. However, the reaction quickly stops after a very short time. This is caused by the fact that calcium sulfate is insoluble. This insoluble calcium sulfate soon forms a layer on the surface of the marble chips, stopping any further reaction.

This reaction emphasises that some salts are insoluble in water, e.g. silver chloride and barium sulfate. Such salts cannot be made by the crystallisation methods we have described earlier. They are generally made by **precipitation**.

For example, barium sulfate can be made by taking a solution of a soluble sulfate (e.g. sodium sulfate). This is added to a solution of a soluble barium salt (e.g. barium chloride). The insoluble white solid, barium sulfate, is formed immediately. This solid 'falls' to the bottom of the tube or beaker as a precipitate (Figure C7.19). The precipitate can be filtered off. It is then washed with distilled water and dried in a warm oven.

The equation for this reaction is:

$$\underset{\text{chloride}}{\text{barium}} + \underset{\text{sulfate}}{\text{sodium}} \rightarrow \underset{\text{sulfate}}{\text{barium}} + \underset{\text{chloride}}{\text{sodium}}$$

$$BaCl_2(aq) + Na_2SO_4(aq) \rightarrow BaSO_4(s) + 2NaCl(aq)$$

This equation shows the importance of state symbols. It is the only way we can tell that this equation shows a precipitation.

KEY WORD

precipitation: the sudden formation of a solid when either two solutions are mixed or a gas is bubbled into a solution.

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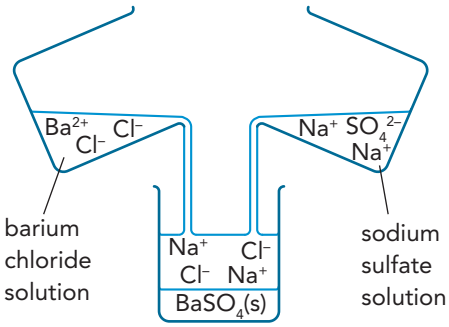

Ba^{2+} and SO_4^{2-} ions combine to form a precipitate of $BaSO_4$; the Na^+ and Cl^- ions stay in solution.

Figure C7.19: Precipitation of barium sulfate. The solid can be collected by filtration or centrifugation.

Questions

C7.15 What do the following terms mean in connection with chemical reactions to produce salts?

a precipitation **b** titration

c an ionic equation

C7.16 Which of these salts can be prepared by precipitation?

A silver iodide

B magnesium nitrate

C lead(II) chloride

C7.17 The insoluble salt, barium sulfate, can be prepared from a solution of barium nitrate by precipitation.

a Name a soluble salt that could be added to the barium nitrate solution to give a precipitate of barium sulfate.

b What colour is the precipitate of barium sulfate?

PROJECT C7.01 STOP-START GO: WHEN IONS COLLIDE!

'Stop-motion' animations are a popular tool for helping to explain concepts that involve movement. The animations are created by linking a series of individually photographed images. In this project, you are going to create a stop-motion animation of a precipitation reaction.

In a precipitation reaction, solutions containing ions are mixed. The ions are moving in the solutions but when certain ions meet, they combine and fall together out of solution (Figure C7.19). The reaction lends itself to animation as we cannot see the individual ions in solution and how they come together.

In a pair or small group, choose a precipitation reaction to focus on. Figure C7.20 shows the precipitation of silver chloride, but you can choose one of several different reactions (think about the analysis tests in Chapter C12).

You need to produce a storyboard to help you visualise the final animation. This should explain the movement of the ions during the mixing of the two solutions. Your storyboard must include:

1 an image of the two separate solutions before mixing

Figure C7.20: Precipitation of silver chloride.

2 some images of one solution being poured into the other

3 images of the precipitate settling; possibly of it being stirred up and allowed to settle again.

Having produced your storyboard, you should then produce your animation. This can be done in various ways. For example, you could draw some illustrations similar to Figure C7.19 to show diagrammatically how the precipitate forms. Include some pictures of how an ionic equation for the reaction is constructed. Then take a series of photographs, perhaps adding callouts which you can assemble together as a set of slides. You could use a stop-start animation app that will allow you to put together a series of photographs and add a voiceover to describe the process. In both cases, the more photographs you take and the less the movement between them, the better it will look.

If you do not have access to a camera/laptop then you could produce a flipbook with lots of little images showing a precipitation reaction.

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SUMMARY

Acids turn litmus and methyl orange red. Alkalis turn red litmus paper blue and methyl orange yellow.
Bases are the oxides and hydroxides of metals, and soluble bases are also referred to as alkalis.
The relative acidity or alkalinity or pH of a solution can be assessed using the colour observed using universal indicator.
Acids and bases react together in a neutralisation reaction to produce a salt and water only.
Most metal oxides and hydroxides are basic (e.g. CuO and CaO), while many oxides of non-metals can be classified as acidic oxides (e.g. CO_2 and SO_2).
Some metal oxides, such as aluminium oxide and zinc oxide, can react with both acids and alkalis, and are therefore classified as amphoteric oxides.
Acids take part in certain characteristic reactions, such as those with bases (neutralisation), with metals to produce hydrogen and with metal carbonates to form carbon dioxide.
Salts are formed by the replacement of the hydrogen in an acid with a metal.
Some salts are soluble in water while other salts are insoluble. There are general solubility rules that apply to the various different types of salt.
A hydrated substance is a substance that is chemically combined with water. An anhydrous substance is a substance containing no water.
Methods are available for the preparation, separation and purification of soluble salts by the reaction of the parent acid with either excess metal, excess insoluble base or excess insoluble carbonate.
A soluble salt can be prepared by titration of an acid with an alkali followed by separation and purification.
An insoluble salt can be prepared by precipitation followed by filtration.

PRACTICE QUESTIONS

1 Metals and non-metals generally produce different types of oxides when reacted with air or oxygen. **Identify** which row in the table correctly defines the nature of the oxides of the elements listed.

	Forms an acidic oxide	Forms a basic oxide
A	phosphorus	sulfur
B	magnesium	sulfur
C	sulfur	phosphorus
D	sulfur	magnesium

[1]

COMMAND WORD

Identify: name/select/recognise.

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CONTINUED

2 A student tested 50 cm^3 of hydrochloric acid with methyl orange indicator. She then added the hydrochloric acid to powdered calcium carbonate to make carbon dioxide.

a **Give** the colour that the indicator turned. **[1]**

b Give a word equation for the reaction of hydrochloric acid with calcium carbonate; include state symbols. **[2]**

c When carbon dioxide is tested with moist universal indicator paper, the paper turns orange. **Suggest** what this shows about carbon dioxide. **[1]**

d pH is a measure of how acidic or alkaline a substance is. **Describe** how you could use an indicator to find the pH of a solution of calcium hydroxide. **[3]**

[Total: 7]

3 The method of preparing a soluble salt in the laboratory has certain clear stages. Identify the three steps in the table that are needed to make sodium sulfate crystals from sodium hydroxide solution and dilute sulfuric acid.

	First step	Second step	Third step
A	evaporation	crystallisation	neutralisation
B	neutralisation	evaporation	crystallisation
C	neutralisation	crystallisation	evaporation
D	evaporation	neutralisation	crystallisation

4 A list of salts is shown below:

barium sulfate **copper sulfate** **potassium carbonate** **sodium chloride** **zinc nitrate**

Identify the salt that:

a cannot safely be made by reacting acid with a metal **[1]**

b is made by titration **[1]**

c is insoluble **[1]**

d reacts with acid to produce a gas. **[1]**

[Total: 4]

5 Excess magnesium carbonate was added to dilute sulfuric acid to make a sample of magnesium sulfate.

a Suggest an observation that would be made as the reaction took place. **[1]**

b Give a reason for why excess magnesium carbonate was used. **[1]**

c **State** how you would know when the reaction was complete. **[1]**

d **Explain** how you would separate a pure sample of magnesium sulfate from the mixture. **[3]**

[Total: 6]

COMMAND WORDS

give: produce an answer from a given source or recall/memory.

suggest: apply knowledge and understanding to situations where there are a range of valid responses in order to make proposals/put forward considerations.

describe: state the points of a topic/give characteristics and main features.

COMMAND WORDS

state: express in clear terms.

explain: set out purposes or reasons/make the relationships between things clear/say why and/or how and support with relevant evidence.

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CONTINUED

6 A list of copper salts is shown below:

copper carbonate **copper chloride** **copper nitrate** **copper sulfate**

Identify the salt that could be made by the following method.

- mix the solutions of two salts
- filter the mixture
- wash the residue
- dry the residue **[1]**

7 A student wanted to make a sample of the insoluble salt lead(II) chloride.

a Identify *two* substances which could be used to form this salt. **[2]**

b Give the steps the student should use to produce a pure dry sample of lead(II) chloride from these substances. **[4]**

[Total: 6]

SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
describe acids and alkalis in terms of their effect on indicators such as litmus and methyl orange	C7.01			
state that bases are the oxides and hydroxides of metals and that alkalis are soluble bases	C7.01			
compare the relative acidity or alkalinity or pH of solutions using the colour observed using universal indicator	C7.01			
describe how acids and bases react together in a neutralisation reaction	C7.01			
describe the characteristic reactions of acids with bases; and with metals to produce hydrogen; and with metal carbonates to form carbon dioxide	C7.01			
classify metal oxides and hydroxides as basic while many non-metal oxides are acidic oxides	C7.02			
classify some metal oxides such as ZnO and Al_2O_3, as amphoteric as they can react with both acids and alkalis	C7.02			

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CONTINUED

I can	See topic . . .	Needs more work	Almost there	Confident to move on
understand that some salts are soluble in water while others are insoluble	C7.03			
describe hydrated salts as ones containing water and anhydrous salts as those without water	C7.03			
describe the preparation, separation and purification of a soluble salt by reaction of an acid with either excess metal, excess insoluble base or excess insoluble carbonate	C7.03			
describe the preparation, separation and purification of a soluble salt by titration of an acid with an alkali and by separation of an insoluble salt by precipitation	C7.03			
describe the preparation of an insoluble salt by precipitation.	C7.03			

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C8

The Periodic Table

All learners study some content in this chapter

IN THIS CHAPTER YOU WILL:

- recognise that the Periodic Table allows us to classify elements and predict properties of elements
- learn how the elements are organised into a table of periods and groups based on the order of increasing atomic (proton) number
- describe the change from metallic to non-metallic character across a period
- relate chemical properties to electron configuration
- identify trends in groups and make predications given information on the elements
- describe the trends in properties of the Group I alkali metals
- describe the trends in properties of the halogens (Group VII)
- state the reactions of halide ions with halogens
- describe the noble gases (Group VIII) as unreactive, monatomic gases
- describe the key characteristics of the transition elements.

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BEFORE YOU START

Work in groups of three or four and use a copy of the Periodic Table.

1 Make an estimate of how many more metals there are than non-metals, and where they are placed in the Periodic Table.

2 What are the properties you most obviously associate with a metal? Make a list in your group.

3 Discuss the question 'Are all metals magnetic?'. What do you think?

4 If you have a magnet, try to use it on samples of aluminium, copper and magnesium. Can you name the three most important magnetic, metallic elements?

SCIENCE IN CONTEXT C8.01

The women behind the Periodic Table

The modern Periodic Table has been a major scientific achievement involving both men and women. The breakthrough in the organisation of the elements came in 1869 when the Russian chemist Dmitri Ivanovich Mendeleev put forward his ideas of a Periodic Table. In his first attempt he used 32 of the 61 elements known at that time and stressed the idea there was a periodic pattern to the properties of the elements. Mendeleev drew up his table based on atomic masses, but elements of similar mass and character are difficult to distinguish. Mendeleev was in correspondence with Julia Lermontova, a Russian scientist working in Heidelberg and the first woman to obtain a doctorate in chemistry. Her work on separation methods for the platinum group of elements meant that the elements could be properly placed in the Periodic Table. The success of Mendeleev's Periodic Table was mainly due to him leaving gaps in the table for further possible elements and in predicting the properties of elements that had not yet been discovered.

Many women have been involved in the search for new elements. Marie Curie discovered radium and polonium in the 1890s and was the first woman to be awarded a Nobel Prize. Other notable women involved in the discovery of the elements in the last century include Lise Meitner (protactinium in 1917), Ida Noddack (rhenium in 1925) and Marguerite Perey (francium in 1939). Most of these women worked with male collaborators and their contributions were not always fully acknowledged at the time.

Francium was the last element to be discovered in nature and the search for new elements now requires large teams with particle accelerators and big budgets. The work by American chemists Darleane Hoffman and Dawn Shaughnessy helped to discover the most recent six new 'superheavy' elements (elements 113–118) that were officially recognised in 2015.

Clarice Phelps, one of the co-discoverers of tennessine (element 117), is the first African-American woman to discover a new chemical element (Figure C8.01).

Figure C8.01: Clarice Phelps, one of the co-discoverers of tennessine.

The critical role of women in science has been recognised by UNESCO. In 2015, UNESCO established the International Day of Women and Girls in Science, celebrated annually on 11 February, as an opportunity to promote access to and participation in science for women and girls.

Discussion questions

1 Why do you think that much of the early pioneering work by women scientists was not acknowledged at the time?

2 Do you think the situation has changed? Do you think there are obstacles to women and girls participating in science?

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C8.01 Arrangement of elements

Groups and periods

All modern versions of the **Periodic Table** are based on the table proposed by Mendeleev in 1869. We have discussed some aspects of the Periodic Table when describing atomic structure in Chapter C2. It is used to classify elements and make predictions about their properties. An example of the Periodic Table is given in Figure C8.02.

In the Periodic Table:

- elements are arranged in order of increasing proton (atomic) number
- vertical columns of elements with similar properties are called **groups**
- horizontal rows are called **periods**.

KEY WORDS

Periodic Table: a table of elements arranged in order of increasing proton number (atomic number) to show the similarities of the chemical elements with related electronic configurations.

group: vertical column of the Periodic Table containing elements with similar chemical properties; atoms of elements in the same group have the same number of electrons in their outer energy levels.

period: a horizontal row of the Periodic Table.

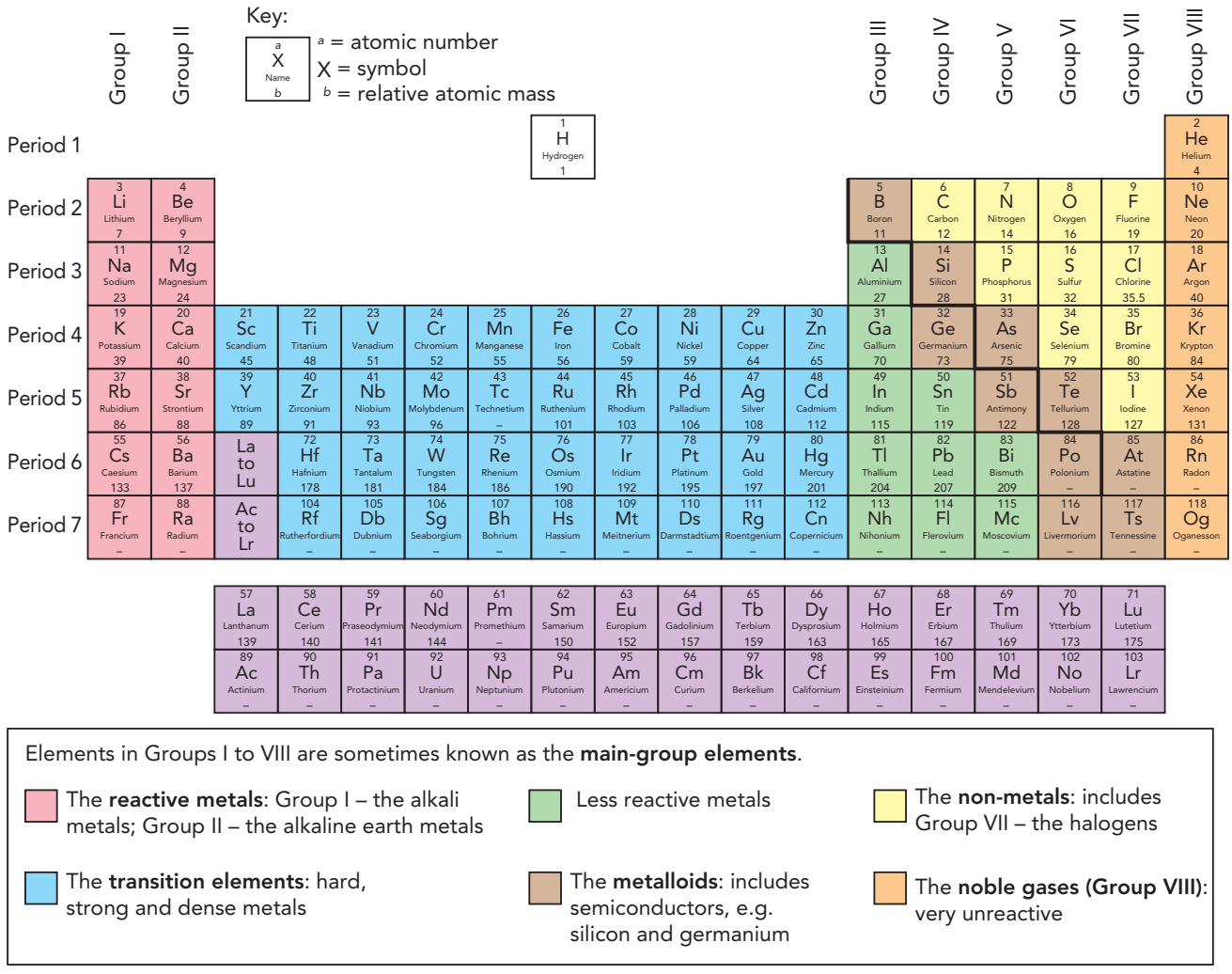

Figure C8.02: Periodic Table showing the major regions.

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Metals and non-metals

The main distinction in the Periodic Table is between metals and non-metals. Metals are clearly separated from non-metals. The non-metals are grouped into the top right-hand region of the Periodic Table, above the thick stepped line in Figure C8.02. One of the first uses of the Periodic Table now becomes clear. Although we may never have seen a sample of the element hafnium (Hf), we know from looking at the Periodic Table that it is a metal. We may also be able to predict some of its properties. The change from metallic to non-metallic properties in the elements across a period is not as clearcut as suggested by drawing the line between the two regions of the Periodic Table. The elements close to the line show properties that lie between these extremes. (We will consider the properties of metals and non-metals in more detail in Chapter C9.) These elements are now often referred to as **metalloids (or semi-metals)**. Such elements have some of the properties of metals and others that are more characteristic of non-metals. There are eight elements that are called metalloids. They often look like metals but are brittle like non-metals. They are neither conductors nor insulators, but make excellent semiconductors. The prime example of this type of element is silicon (Figure C8.03).

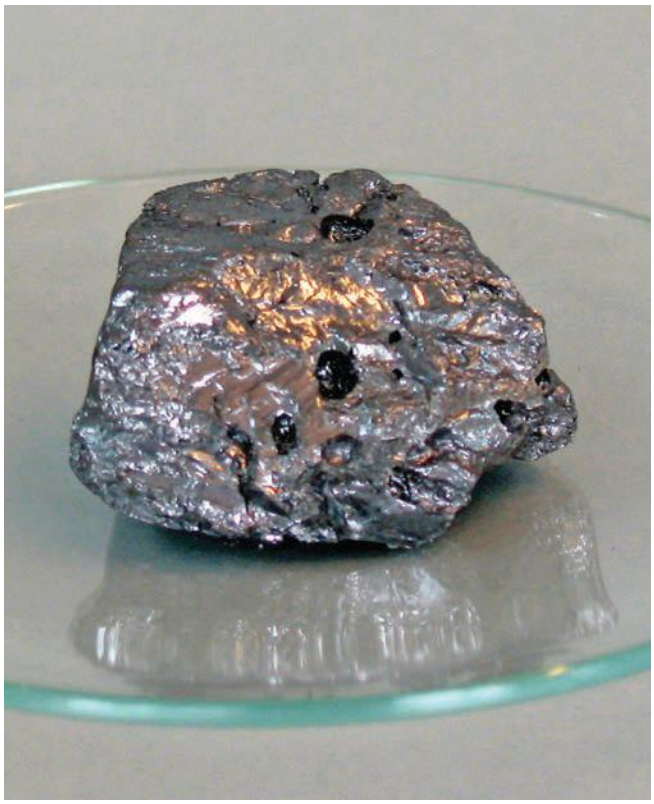

Figure C8.03: A sample of the element silicon, the basis of the semiconductor industry.

KEY WORD

metalloid (semi-metal): element that shows some of the properties of metals and some of non-metals, e.g. boron and silicon.

Position of hydrogen in the Periodic Table

Hydrogen is difficult to place in the Periodic Table. Different versions place it above Group I or Group VII. More often, in modern tables, it is left by itself (Figure C8.04). This is because, as the smallest atom of all, its properties are unique. It does not fit easily into the trends shown in any one group.

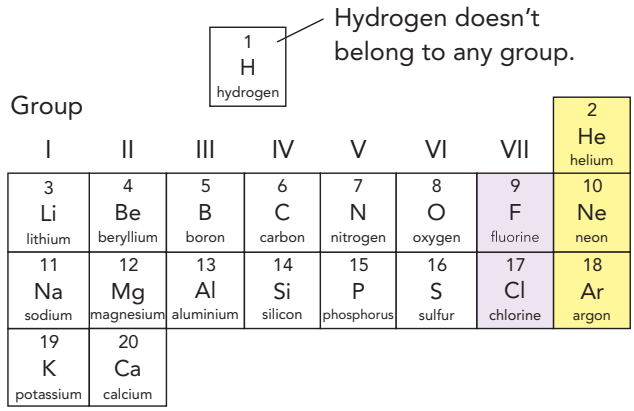

Figure C8.04: Position of hydrogen in the Periodic Table.

Electronic configuration

When the first attempts were made to construct a Periodic Table, the structure of the atom was unknown. The order of the elements was originally provided by their increasing atomic masses. However, it was later found that atomic number provides a better basis for putting the elements in order. Atomic number provides a linear, continuous sequence to listing the elements. This linear arrangement is then arranged into columns based on chemical properties. A periodic property is one that shows a repeating pattern in the Periodic Table.

We can now directly link the properties of an element with its position in the Periodic Table and its electronic configuration (Figure C8.05). The number of outer electrons in the atoms of each element has been found. Elements in the same group of the Periodic Table have the same number of outer electrons. We also know that, as you move across a period in the Periodic Table, a shell of electrons is being filled. Each period in the Periodic Table represents the filling of an electron shell.

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There is a clear relationship between electron arrangement and position in the Periodic Table for the main-group elements.

- Elements in the same group have the same number of electrons in their outer shell. For the main-group elements, the number of the group is the number of electrons in the outer shell.
- Periods of the Periodic Table also have numbers. This number shows us how many shells of electrons the atom has.

A magnesium atom, for example, has two electrons in its third, outer, shell, and is in Group II and Period 3 (Figure C8.05).

It is the outer electrons of an atom that are mainly responsible for the chemical properties of any element. Therefore, elements in the same group will have similar properties. Certain electron arrangements are found to be more stable than others. This makes them more difficult to break up. The most stable arrangements are those of Group VIII, and this explains why they are so unreactive.

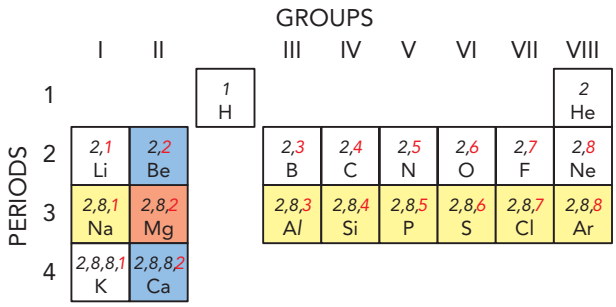

Figure C8.05: Relationship between an element's position in the Periodic Table and the electronic configuration of its atoms.

Group trends

There are links between the organisation of particles in the atom and the regular variation in properties of the elements in the Periodic Table. This means that we can see certain broad trends in the Periodic Table (Figure C8.06). These trends become most obvious if we leave aside the noble gases in Group VIII. Individual groups show certain 'group characteristics'. These properties follow a trend in particular groups.

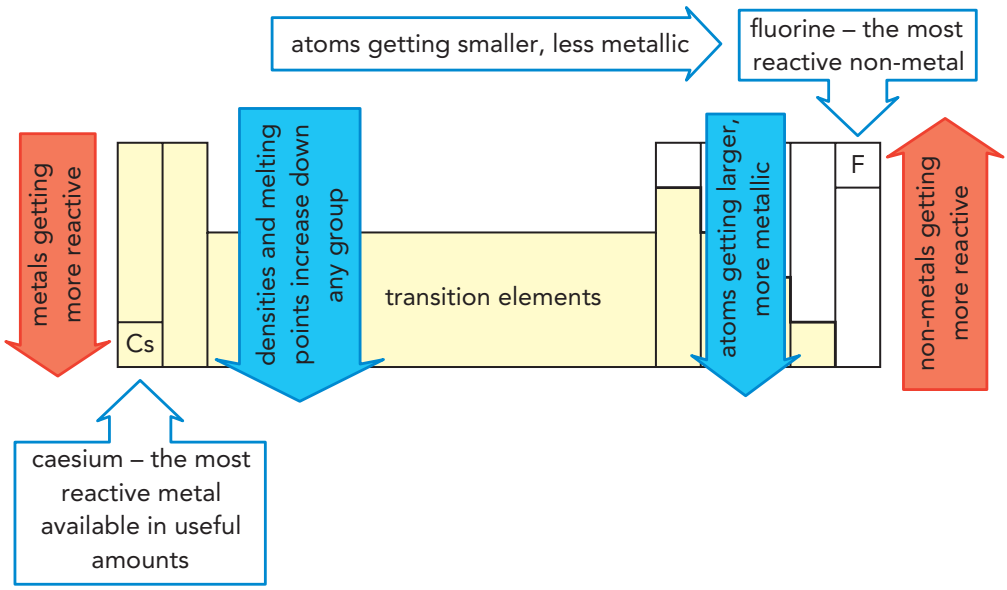

Figure C8.06: General trends in the Periodic Table, leaving aside the noble gases in Group VIII.

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ACTIVITY C8.01

Discovering elementary patterns!

In groups, organise yourselves as a team of news reporters working on a breakthrough in organising a table of the elements, or the discovery of a new element, celebrating this scientific progress.

Write a news blog celebrating the achievement of a scientist of your choice. You could choose a person from the history of chemistry (e.g. Mendeleev, Marie Curie or William Ramsay) or someone involved in the recent discoveries of new elements (e.g. Glenn Seaborg, Dawn Shaughnessy or Clarice Phelps).

Research the scientist of your choice and the context of their work. Remember that this is a news report, so does not need to be too technical.

Once you have written your blog post, get together with another group, swap reports and complete the following peer assessment.

Peer assessment

When you have swapped blog reports with another group, discuss the following questions.

Does their blog post include:

1. a catchy/engaging heading?
2. a concise and clear introduction?
3. specific facts and information about their chosen scientist and their achievement?
4. the group's own opinion on the achievement?

Now, write down the answers to the following questions to give some feedback to the other group:

- What do you think they did well?
- Next time they write a news blog, what could they do to improve?

REFLECTION

Having worked with others on Activity C8.01, consider whether you found group work helped you in your learning. Were you able to contribute confidently to the group discussion and appreciate the input of others to it? What would you do differently to gain more from this type of activity in future?

C8.02 Group I properties

The metals in Group I are often called the **alkali metals**. They are soft solids with relatively low melting points and low densities (Figure C8.07). They are highly reactive and are stored in oil to prevent them reacting with the oxygen and water vapour in the air. When freshly cut with a knife, all these metals have a light-grey, silvery surface, which quickly tarnishes and becomes dull.

KEY WORDS

alkali metals: elements in Group I of the Periodic Table; form an alkaline solution when reacted with water; generally the most reactive group of metals.

Figure C8.07: All alkali metals are soft solids and can be cut with a knife. This is a sample of lithium.

The physical properties of the alkali metals change as we go down the group as shown in Table C8.01. The melting points become lower and the density of the metals increases.

There are several different trends down this group of elements:

- melting points and boiling points decrease down the group
- metals get softer as we go down the group
- densities increase as we go down the group (although this trend is obscured in Table C8.01 because the value for sodium is higher than would be expected; see footnote to table).

Observing the trends in these values for physical properties means we can predict values for other elements in Group I. For instance, we would predict the melting point of rubidium to be lower than that of potassium by about 20–30 °C as the gap between melting points is getting smaller at each step. This would suggest a value of between 33–43 °C. The actual value is 39 °C.

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Chemical **reactivity** increases as we go down the group. All Group I metals react with cold water to form hydrogen and an alkaline solution of the metal hydroxide. They are known as the alkali metals because they react vigorously with water to produce hydrogen and an alkaline solution. The equation for the reaction between sodium and water is:

sodium + water → sodium hydroxide + hydrogen

$2Na + 2H_2O \rightarrow 2NaOH + H_2$

The production of an alkaline solution can be shown by adding a few drops of universal indicator to the water. The solution will turn the water purple if an alkali is produced. The reactions range from vigorous in the case of lithium to explosive in the case of caesium. The strength of the reaction of each metal can be judged by several observations (Table C8.02). Observations such as the production of a gas, whether the metal melts on contact with the water and whether the gas produced is ignited all give an indication of how vigorous the reaction is.

Questions

C8.01 What is the name of the alkali formed when potassium reacts with water?

C8.02 Write a word equation for the reaction between lithium and water.

C8.03 Using the information in Tables C8.01 and C8.02:

a Suggest a value for the melting point of rubidium.

b Suggest how the reactivity of rubidium with water compares with potassium.

C8.03 Group VII properties

The most reactive non-metals are the **halogens**, found in Group VII of the Periodic Table (Figure C8.08). These exist as diatomic molecules, pairs of atoms. In contrast with Group I, in Group VII reactivity decreases down the group. For example, fluorine is a dangerously reactive, pale-yellow gas at room temperature. There is a steady increase in melting points and boiling points, as well as the density, as we go down the group, and the elements change from gases to solids as the atomic number increases. Interestingly, the lowest element in this group is also a highly radioactive and rare element, astatine. The actual properties of astatine remain a mystery to us, but we could make a good guess at some of them.

KEY WORDS

reactivity: the ease with which a chemical substance takes part in a chemical reaction.

halogen: element in Group VII of the Periodic Table; generally the most reactive group of non-metals.

Metal	Electronic configuration	Density / g/cm^3	Melting point / °C	Boiling point / °C	Hardness
lithium	2,1	0.53	181	1342	fairly soft
sodium	2,8,1	0.97	98	883	soft
potassium	2,8,8,1	0.86*	63	760	very soft

** the densities of rubidium and caesium are 1.53 and 1.88, respectively.*

Table C8.01: Physical properties of some alkali metals.

Alkali metal	Gas production	Heat produced by reaction	Production of alkaline solution	Production of flame
lithium	fizzes slowly, a few bubbles	moves slowly on the surface, does not melt	metal disappears slowly, solution turns purple	no flame
sodium	fizzes strongly, many bubbles	melts into a ball on surface and moves about	metal disappears quickly, solution turns purple	no flame unless held in place
potassium	fizzes violently, very many bubbles	melts and moves very quickly on surface	disappears very quickly, solution turns purple	hydrogen ignites, a lilac flame produced

Table C8.02: Observations on the reactions of the alkali metals with water (with universal indicator added).

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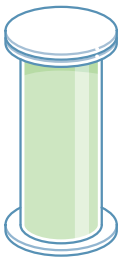
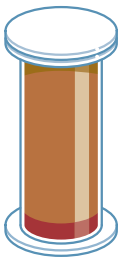
Cambridge University Press



Chlorine (Cl_2)

- dense pale yellow-green gas
- smelly and poisonous
- occurs as chlorides, especially sodium chloride in the sea
- relative atomic mass 35.5



Bromine (Br_2)

- red–brown liquid with red–brown vapour
- smelly and poisonous
- occurs as bromides, especially magnesium bromide in the sea
- relative atomic mass 80

Iodine (I_2)

- grey–black solid with purple vapour
- smelly and poisonous
- occurs as iodides and iodates in some rocks and in seaweed
- relative atomic mass 127

Figure C8.08: General properties of some of the halogens (Group VII).

The halogen family found in Group VII of the Periodic Table shows clear similarities between the elements of the group. The common properties of the halogens are:

- They are all poisonous and have a similar strong smell.
- They are all non-metals.
- They all form diatomic molecules (e.g. Cl_2, Br_2 and I_2).
- They all have a valency of 1 and form compounds (**halides**) with similar formulae, e.g. hydrogen chloride (HCl), hydrogen bromide (HBr) and hydrogen iodide (HI).

There are gradual changes in properties between the halogens (Figure C8.09). As you go down the group, the boiling points increase (Table C8.03), as do the densities. The physical state of the halogens changes from gas to liquid to solid going down the group. The intensity of the colour of the element also increases, from pale to dark. Following these trends, it should not surprise you to know that fluorine is a pale-yellow gas at room temperature.

Halogen displacement reactions

The **halogen displacement reactions** shown in Table C8.04 demonstrate the order of reactivity of the three major halogens. For example, if you add chlorine to a solution of potassium bromide, the chlorine displaces bromine (Figure C8.09). Chlorine is more reactive than bromine, so it replaces bromine and potassium chloride is formed. Potassium bromide solution is colourless. It turns orange when chlorine is bubbled through it:

$$\underset{}{Cl_2} + \underset{\text{colourless}}{2KBr} \rightarrow 2KCl + \underset{\text{orange}}{Br_2}$$

Chlorine will also displace iodine from potassium iodide:

$$\underset{}{Cl_2} + \underset{\text{colourless}}{2KI} \rightarrow 2KCl + \underset{\text{yellow–brown}}{I_2}$$

KEY WORDS

halides: compounds formed between an element and a halogen, e.g. sodium iodide.

halogen displacement reactions: reactions in which a more reactive halogen displaces a less reactive halogen from a solution of its salt.

Halogen	Electronic configuration	Melting point / °C	Boiling point / °C	State at r.t.p.	Colour
chlorine	2,8,7	−101	−35	gas	pale-yellow–green
bromine	2,8,18,7	−7	+59	liquid	red–brown
iodine	2,8,18,18,7	+114	+184	solid	grey–black

Table C8.03: Physical properties of some halogens.

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Reaction with	Chlorine	Bromine	Iodine
chlorides		no reaction	no reaction
bromides	displaces bromine, e.g. $Cl_2 + 2KBr \rightarrow 2KCl + Br_2$		no reaction
iodides	displaces iodine, e.g. $Cl_2 + 2KI \rightarrow 2KCl + I_2$	displaces iodine, e.g. $Br_2 + 2KI \rightarrow 2KBr + I_2$	

Table C8.04: Some reactions of the halogens.

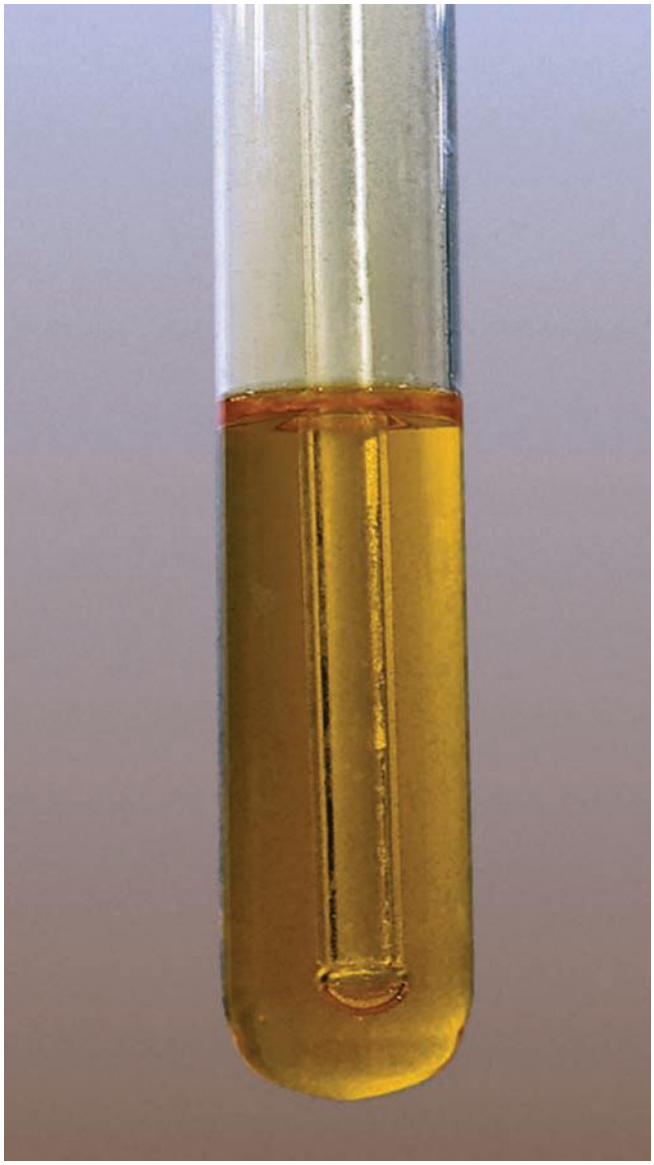

Figure C8.09: Bromine is displaced by chlorine from a colourless solution of potassium bromide.

C8.04 Transition elements

If we look at period 4 in the Periodic Table, we see that there is a whole 'block' of elements in the centre of the Periodic Table. This block of elements falls outside the main groups of elements that we have talked about so far. They are best considered not as a vertical group of elements but as a block. They are usually referred to as the transition elements (or transition metals). Their properties make them among the most useful metallic elements available to us. They are much less reactive than the metals in Groups I and II. Many have excellent corrosion resistance, for example chromium. The very high melting point of tungsten (3410 °C) led to its use in the filaments of incandescent light bulbs.

Many familiar objects are made from transition metals. Figure C8.10 shows a range of these objects, including iron nails, a vanadium spanner, silver cutlery, gold jack plugs, copper pipe joints, an iron magnet, a titanium camera body and chromium-plated balls on the Newton's cradle.

Figure C8.10: Some everyday objects made from transition metals.

These general properties mean that the transition metals are useful in a number of different ways. In addition, there are particular properties that make these metals distinctive. Transition elements have variable oxidation states and often produce coloured compounds (Figure C8.11).

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Coloured transition metal salts dissolve to give coloured solutions.

Figure C8.11: Many of the compounds of transition metals are coloured and, when they dissolve, they give coloured solutions.

Transition metals can also act as catalysts. This means that they can be added to a reaction to speed it up without themselves being used up. Examples include iron as a catalyst for making ammonia in the Haber process and platinum and rhodium in a catalytic converter.

General features of transition metals:

- They are hard and strong.
- They have high density.
- They have high melting and boiling points.

Distinctive properties of transition metals:

- Many of their compounds are coloured (Figure C8.11).
- The transition metals, or their compounds, often act as catalysts.

C8.05 The noble gases

When Mendeleev first constructed his table, part of his triumph was to predict the existence and properties of some undiscovered elements. However, there was no indication that a whole group of elements (Group VIII) remained to be discovered! Because of their lack of reactivity, there was no clear sign of their existence. However, analysis of the gases in air (Chapter C10) by John William Strutt (Lord Rayleigh) led to the discovery of argon in 1894. There was no suitable place in the Periodic Table for an individual element with argon's properties. This pointed to the existence of an entirely new group. Helium, which had first been detected by spectroscopy of light from the Sun during an eclipse, and other noble gases in the group (Group VIII) were isolated by Sir William Ramsay in the 1890s. The radioactive gas, radon, was the last to be purified, in 1909.

All of the noble gases are present in the Earth's atmosphere. Together they make up about 1% of the total, though argon is the most common. These gases are particularly unreactive. The atoms of the noble gases do not combine with each other to form molecules or any other form of structure. This is because they have a complete outer shell of eight electrons.

All these properties point to the atoms of the noble gases being particularly stable:

- The electronic configurations of the atoms of the noble gases are energetically very stable.
- This means that they do not react readily with other atoms and generally exist as single atoms.

Questions

C8.04 Which halogen(s) will displace bromine from a solution of potassium bromide?

C8.05 What is the similarity in the electron arrangement of the noble gases?

C8.06 State *four* differences between an alkali metal and a transition metal such as nickel.

C8.07 Which phrase (A–D) completes the following statement?

All transition metals in their compounds …

A … are white in colour

B … are magnetic

C … form ions of the type M^{2+} and M^{3+}

D … often act as catalysts.

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PROJECT C8.01 ELEMENTS CARD GAME

This is a card game in which two people compete with each other on a chosen value in a set of cards featuring a particular collection of objects; in this case the elements. In groups, make a set of cards based on the first 36 elements of the Periodic Table.

Figure C8.12 shows a suggested set of information to enter on the cards, although you could add in further or alternative information (but do make it relevant to your learning).

Symbol: **Li**

Name: **Lithium**

Atomic number: **3**

Mass number: **7**

Group: **I**

Period: **2**

Physical state at r.t.: **Solid**

Figure C8.12: Suggested layout for an elements card – probably not a winning one!

Having made the cards, deal out a set of cards between a pair of you and challenge each other according to the following criteria:

- for names and symbols – alphabetical precedence wins
- for numbers – the higher number wins
- for physical state – solid beats gas; with the one liquid trumping all.

As you work through the game you can ask each other questions about the cards you are currently challenging with. For example, which element is the more reactive of the two elements, what is the electronic arrangement of the atoms, and so on.

Use the game to reinforce your familiarity with the elements.

SUMMARY

The chemical elements can be organised into the Periodic Table based on increasing atomic (proton) number.
There is a trend from metallic to non-metallic character in the properties of the elements as we move across a period in the Periodic Table.
The chemical properties of a group are similar due to their electronic arrangement.
The chemical and physical properties of the Group I alkali metals vary as we descend the group.
Group VII shows trends in physical properties down the group.
Group VII elements can undergo displacement reactions.
We can predict the properties of elements given information about other members of the group.
The transition elements (transition metals) have certain common key characteristics.
The noble gases (Group VIII) are unreactive, monatomic gases because they have eight electrons in their outer shells.

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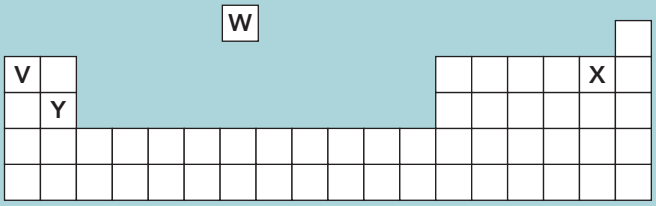
PRACTICE QUESTIONS

1 The figure shows an outline of the Periodic Table with certain elements marked.



Identify which combination of the elements **V**, **W**, **X** or **Y** in the table is a metal and a non-metal.

	Non-metal	Metal
A	Y	V
B	Y	X
C	W	X
D	W	V

[1]

2 The reactivity of elements within a group in the Periodic Table changes with their position in the group. Identify which combination in the table shows the order of increasing reactivity of elements in Group I and Group VII.

	Group I	Group VII
A	Cs → Li	F → I
B	Li → Cs	I → F
C	Li → Cs	F → I
D	Cs → Li	I → F

[1]

3 The table shows part of two groups of the Periodic Table.

Group I	Group VII
lithium, **Li**	
sodium, **Na**	chlorine, **Cl**
potassium, **K**	bromine, **Br**
	iodine, **I**

From the elements given, identify:

a a solid Group VII element **[1]**

b the Group I element with the lowest density **[1]**

c an element that is a liquid at room temperature **[1]**

d the *two* elements that would react most violently with each other. **[2]**

[Total: 5]

COMMAND WORD

identify: name/select/recognise.

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CONTINUED

4 a **State** whether transition elements have high or low densities. [1]

b State whether transition elements are all gases or all metals. [1]

c **Give** the name of the group that includes the elements helium, neon, and argon. [1]

[Total: 3]

COMMAND WORD

state: express in clear terms.

give: produce an answer from a given source or recall/memory.

SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
understand how the elements in the Periodic Table are organised in order of increasing atomic number and into groups and periods	C8.01			
explain the similarities of elements in the same group in terms of their chemical properties	C8.01			
describe the change from metallic to non-metallic character of the elements across a period	C8.01			
identify trends in groups, given information about the elements present	C8.01, C8.02, C8.03			
describe the trend in physical and chemical properties of the alkali metals (Group I)	C8.02			
describe the trend in physical properties of the halogens (Group VII)	C8.03			
describe the displacement reactions of the halogens (Group VII)	C8.03			
describe the key characteristics of the transition elements (transition metals)	C8.04			
describe the properties of the noble gases (Group VIII).	C8.05			

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C9 Metals

All learners study some content in this chapter

IN THIS CHAPTER YOU WILL:

- understand the differences in the physical properties of metals and non-metals
- explore and appreciate the usefulness of metallic elements
- learn that alloys are mixtures of metals with other elements
- learn how diagrams can be used to represent the physical structure of alloys
- understand the uses of certain alloys in terms of their physical properties
- consider how alloys can be harder or stronger than pure metals
- establish the concept of a reactivity series
- analyse how different metals show differences in the strength of their reaction with water, dilute acid and the reduction of their oxides with carbon
- learn how this reactivity relates to the reactivity series and predict an order of reactivity, given a set of experimental results
- understand that the reactivity series relates to the ease with which a metal forms its positive ion by considering the displacement reactions of metals
- discuss the causes of rusting and describe some barrier methods of rust prevention
- consider galvanisation and sacrificial protection as methods of rust prevention
- describe how unreactive metals are found as pure metals, moderately reactive metals can be extracted by reduction with carbon in a blast furnace, while reactive metals are extracted by electrolysis
- learn that aluminium is extracted from bauxite by the electrolysis of molten aluminium oxide
- learn that iron is extracted from hematite by reduction in a blast furnace
- describe how iron is extracted from hematite in a blast furnace, consider the chemistry of the extraction of iron.

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BEFORE YOU START

Metals, and structures made from them, play an important part in our lives.

1 Take a look at the immediate environment around you. What objects do you see that are made using metals?

2 How many different metals can you list that are being used in those objects?

3 Working with a partner, discuss the term 'alloy'.

   a Where have you heard the term before?

   b What do you think an alloy is?

Be ready to share your ideas with others in the class.

SCIENCE IN CONTEXT C9.01

Mining the ocean floor

Concern over the impact of global warming and climate change has focused considerable attention on the need to reduce our use of fossil fuels. One aspect of this is the potential to use electric battery powered cars and this has placed an important focus on improved battery technology. Currently, the metal cobalt is an essential ingredient for the rechargeable batteries needed to provide electric cars with the needed power and storage capacity. Demand for cobalt is therefore increasing rapidly and the number of sites where cobalt can be mined worldwide is very limited. Most of the world's cobalt is mined in the Democratic Republic of the Congo.

Expanding production is not straightforward and this is leading mining companies to consider obtaining cobalt from a very different location – the deep-sea floor!

We are becoming increasingly aware of rocks on the seabed, known as 'polymetallic nodules', that are rich in metals such as manganese, nickel and cobalt (Figure C9.01). The discovery of this potential resource has raised enthusiastic attention over recent years. Different regions of the seabed have been put forward as open to exploitation. Prototype mining machines have been designed and the pressure is growing to develop mining operations, given the increasingly pressing need for these rare metals.

But what would be the environmental cost of such deep-sea mining? Gathering these nodules from the seabed would disturb the habitat of the marine life, stirring up clouds of sand and silt. New technology is being designed to reduce the impact of what is effectively open-cast mining, but it surely cannot eliminate all damage. There is significant international interest even though the financial costs are great and there is need for international control of this development.

Figure C9.01: A manganese nodule of the type found on the ocean floor.

Discussion questions

1 What are the environmental advantages and disadvantages of developing seabed mining? Think as broadly as you can about the related issues.

2 What are the problems associated with relying on one major land-based source for a resource that is likely to be in increasing demand?

ISBN 9781009311281

C9.01 Properties of metals

Physical properties of metals and non-metals

The majority of elements within the Periodic Table can be classified as metals. They are positioned to the left in the Periodic Table (Figure C9.02). The metals form a group of elements whose structures are held together by metallic bonding (discussed further later in this section). This type of bonding gives rise to many properties that the metals have in common. However, there is wide variation in the level of these properties when we look in detail at different metals. For instance, many metals have a high density (e.g. iron), but the alkali metals (Group I) have low densities (Chapter C8).

The best way to identify a metal or non-metal is to check whether it conducts electricity or not. The simple apparatus for doing this was shown as the method for testing the electrical conductivity of a solid in Chapter C4. A simple circuit is set up and any current flow is detected by a bulb (or measured by an ammeter).

All metals conduct electricity, even mercury, which is liquid at room temperature. All non-metals, except graphite, do not conduct electricity. Together with electrical conductivity, **malleability**, high melting and boiling points and **thermal conductivity** are the other physical properties that most clearly characterise a metal.

These physical properties of metals can be explained by the metallic bonding (Chapter C2) present. As metal atoms have relatively few electrons in their outer shells, when they are packed together, each metal atom loses its outer electrons into a 'sea' of delocalised electrons. Delocalised means the electrons are not restricted to orbiting one positive ion.

Having lost electrons, the atoms present are no longer electrically neutral. They become positive ions because they have lost electrons but the number of protons in the nucleus has remained unchanged. Therefore, the structure of a metal is made up of positive ions packed together. These ions are surrounded by electrons, which can move freely between the ions. These delocalised electrons form a kind of electrostatic 'glue' holding the structure together (Figure C9.03).

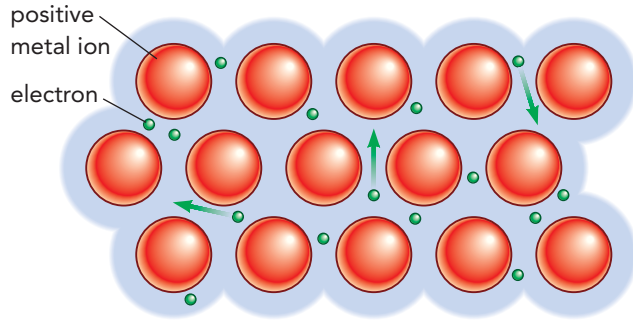

Figure C9.03: In metallic bonding, the metal ions are surrounded by a 'sea' of delocalised electrons that are free to move about.

KEY WORDS

malleability: the ability of a substance to be bent or beaten into shape. Malleable is the word used to describe a substance that can be bent or beaten into shape.

thermal conductivity: the ability to conduct heat.

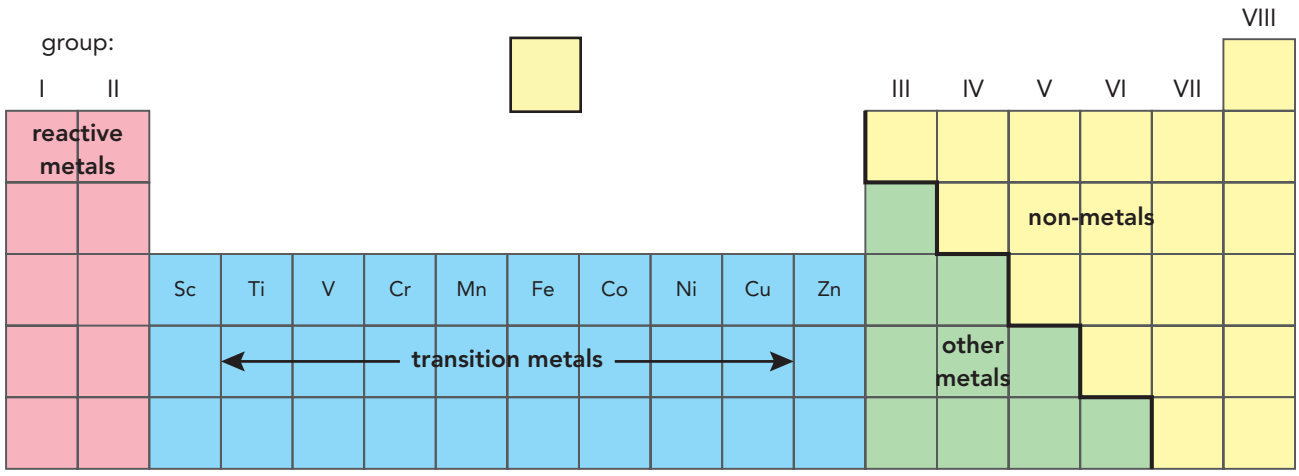

Figure C9.02: Distribution of metals and non-metals in the Periodic Table.

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The key physical properties of metals can be explained using the model of metallic structure and bonding:

- Metals are good conductors of electricity. In an electrical circuit, metals can conduct electricity because the mobile electrons can move through the structure, carrying the current. This type of bonding is present in **alloys** as well. Alloys such as solder and **brass**, for example, will conduct electricity.
- Metals are easily bent and shaped (malleable). The positive ions in a metal are arranged in layers. When a force is applied, the layers can slide over each other. The attractive forces in metallic bonding act in all directions to hold the structure together. This means that when the layers slide over each other new bonds are easily formed (Figure C9.04). This movement of layers leaves the metal with a different shape.

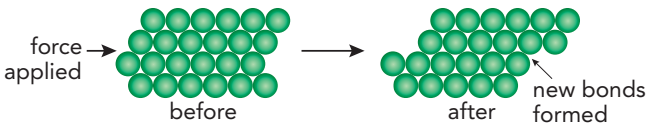

Figure C9.04: When a force is applied to a metal, the layers can slide over each other without the structure being broken.

KEY WORDS

alloys: mixtures of elements (usually metals) designed to have the properties useful for a particular purpose, e.g. solder (an alloy of tin and lead) has a low melting point.

brass: an alloy of copper and zinc; this alloy is hard.

These important physical properties that all metals show to a greater or lesser extent are directly related to their structural characteristics. Table C9.01 presents a summary of the differences in some of the physical properties of metals and non-metals.

Questions

C9.01 Sort the properties in the box into two sets.

a Those that are characteristic of a metal.

b Those typical of a non-metal.

is an insulator	can be beaten into sheets
can be drawn into wires	conducts heat well
conducts electricity well	poor thermal conductor

C9.02 State the names of the following.

a A non-metal that conducts electricity.

b *Two* metals that are soft.

c A metal that is liquid at room temperature.

d A non-metal that conducts heat well.

C9.03 List the *three* properties that most clearly help you to tell the difference between a metal and a non-metal. Explain how the structure of a metal gives rise to any *two* of these properties.

KEY WORD

ductile: a word used to describe the property that metals can be drawn out and stretched into wires.

Physical property	Metals	Non-metals
melting points and boiling points	metals are usually solids (except for mercury, which is a liquid) at room temperature; many metals have high melting and boiling points	non-metals are solids or gases at room temperature (except for bromine, which is a liquid); their melting and boiling points are often low
electrical conductivity	all metals are good conductors of electricity	non-metals are poor conductors of electricity (except for graphite); they tend to be insulators
thermal conductivity	metals are good conductors of heat	non-metals are generally poor thermal conductors (except diamond, which conducts heat strongly)
malleability and ductility	the shape of a piece of metal can be changed by hammering (they are malleable); they can also be pulled out into wires (they are **ductile**)	non-metals are not malleable; they are brittle and break easily when hit

Table C9.01: How the properties of metals and non-metals differ.

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REFLECTION

What learning strategies have you used to investigate the link between metallic bonding and metallic properties? Do you find it useful to create summary diagrams or bullet point lists of the key points?

Chemical properties of metals

The chemical properties of metals and non-metals are also very different, which makes the distinction between these two types of substances very important. Metals show some characteristic reactions with common reagents such as water, oxygen and acids. However, the strength and rate of these reactions varies greatly depending on the particular metal considered. We have seen in Chapter C8 that there are variations in the reactivity of metals as one goes down a particular group of the Periodic Table. The reactivity of the Group I alkali metals with water increases as we go down the group. Also, we saw that the transition elements (transition metals) are less reactive than the alkali metals.

Sodium reacts violently with both air and water. Iron, on the other hand, reacts much more slowly with air and water, producing rust. Gold remains unchanged in the presence of air and water.

Looking in more detail at these basic reactions reveals a pattern of reactivity among metals which will be discussed later.

Table C9.02 summarises the reactions of certain metals with air, water, steam and dilute acid. A gradual decrease in reactivity can be seen moving down the table from the highly reactive (sodium and calcium) to the unreactive (copper, silver and gold). Note that the true reactivity of aluminium is only seen if its protective oxide layer is removed.

It is useful to look in more detail at the reactions of particular metals with water, steam and dilute hydrochloric acid.

Reactions of metals with water/steam

Reactive metals such as potassium, sodium and calcium all react with cold water to produce the metal hydroxide and hydrogen gas.

metal + water → metal hydroxide + hydrogen

For example:

sodium + water → sodium hydroxide + hydrogen

$2Na(s) + 2H_2O(l) \rightarrow 2NaOH(aq) + H_2(g)$

calcium + water → calcium hydroxide + hydrogen

$Ca(s) + 2H_2O(l) \rightarrow Ca(OH)_2(aq) + H_2(g)$

Metal	Reaction with …	
	Water/steam	Dilute HCl
sodium	react with cold water to give hydrogen	react very strongly to give hydrogen
calcium		
magnesium*		
aluminium**	react with steam, when heated, to give hydrogen	react less strongly to give hydrogen
zinc		
iron		
lead	do not react	do not react
copper		
silver	do not react	do not react
gold		

** Reaction of magnesium with water only occurs if the magnesium hydroxide layer is removed. Often no reaction is observed.*

*** These reactions only occur if the protective oxide layer is removed from the aluminium.*

Table C9.02: Reactions of metals with air, water and dilute hydrochloric acid.

Magnesium only reacts very slowly in cold water. However, a much more vigorous reaction takes place if steam is passed over heated magnesium. The magnesium glows brightly to form hydrogen and magnesium oxide. The hydrogen given off can be burnt when lit with a splint.

magnesium + steam → magnesium oxide + hydrogen

$Mg(s) + H_2O(g) \rightarrow MgO(s) + H_2(g)$

Zinc and iron will react in a similar way if steam is passed over the heated metal.

Iron + steam → iron oxide + hydrogen

$3Fe(s) + 4H_2O(g) \rightarrow Fe_3O_4(s) + 4H_2(g)$

Hydrogen gas is produced in all these reactions. You should note that in these cases it is the metal oxide, not the hydroxide, that is formed.

In summary:

- If a metal reacts with cold water, a metal hydroxide and hydrogen are formed.
- If a metal reacts only with steam, then a metal oxide is formed.

Reactions of metals with dilute hydrochloric acid

Moderately reactive metals such as magnesium, zinc or iron can be reacted safely with dilute acids to produce hydrogen gas (Figure C9.05).

metal + hydrochloric acid → metal chloride + hydrogen

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For example:

iron + hydrochloric acid → iron(II) chloride + hydrogen

$Fe(s) + 2HCl(aq) \rightarrow FeCl_2(aq) + H_2(g)$

zinc + hydrochloric acid → zinc chloride + hydrogen

$Zn(s) + 2HCl(aq) \rightarrow ZnCl_2(aq) + H_2(g)$

Figure C9.05: The reaction between zinc and dilute hydrochloric acid produces hydrogen gas.

Questions

C9.04 A word equation is shown here:

$$\text{magnesium} + \text{hydrochloric acid} \rightarrow \text{magnesium chloride} + \text{hydrogen}$$

What is the symbol equation for this reaction?

A $2Mg + HCl \rightarrow MgCl_2 + H_2$

B $Mg + 2HCl \rightarrow MgCl_2 + H_2$

C $Mg + HCl \rightarrow MgCl_2 + H_2$

D $2Mg + 2HCl \rightarrow MgCl_2 + H_2$

C9.05 Select from this list *two* metals that will not react with hydrochloric acid to produce hydrogen:

zinc, copper, iron, magnesium, silver

C9.06 **a** Some metals react with cold water. Copy and complete the general word equation for this type of reaction.

metal + water → metal _____ + _____

b Other metals do not react with cold water but do react when steam is passed over the heated metal. Copy and complete the general word equation for this type of reaction.

metal + steam → metal _____ + _____

c **i** Write the chemical equation for the reaction when steam is passed over heated magnesium.

ii Balance the following equation for the reaction between iron wire and steam.

$$\_\_\_\_Fe + \_\_\_\_H_2O \rightarrow Fe_3O_4 + \_\_\_\_H_2$$

C9.02 Uses of metals

The production of iron dates back to Middle Eastern cultures in the Middle Bronze Age. It then spread through India and China (Figure C9.06). The skills of the smiths and metalworkers stretch back through history. For example, the 'art' of making the blades of Samurai swords, forged from traditional Japanese steel, involves processes of heat treatment and folding that is truly astounding. Such technology grew out of practical understanding. It gave rise to a whole series of techniques and alloys that produced metals fit for a purpose. This expertise has now been added to as the structure of metals has been increasingly understood. We now have a wide range of steels and other alloys suited to demanding uses.

Uses of aluminium

Aluminium was, for a long time, an expensive and little-used metal. In France, around the 1860s, at the Court of Napoleon III (the nephew of Napoleon Bonaparte), honoured guests used cutlery made of aluminium rather than gold. The breakthrough in its usefulness came in 1886 when Charles Hall and Paul Héroult independently found a way to obtain the metal by electrolysis (Chapter C4).

Aluminium is a light, strong metal and has good electrical conductivity. Increasingly, aluminium is used for construction purposes. It is used in the construction of some naval vessels and modern cars.

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Figure C9.06: The Iron Pillar of Delhi dates from the beginning of the 5th century and is remarkable for its resistance to rusting.

It is commonly used in aeroplanes, where it is usually alloyed with other metals such as copper (Figure C9.07). Its low density and good conductivity have also led to its use in overhead power lines. The aluminium is very resistant to corrosion and its low density prevents sagging of the cables between pylons.

Aluminium is particularly useful because it is protected from corrosion by the stable layer of aluminium oxide that forms on its surface. This protective layer stops the aluminium (a reactive metal) from reacting. This makes aluminium foil containers ideal for food packaging because they resist corrosion by natural acids present in the food. Aluminium is also used for external structures such as window frames because the metal resists weathering.

Figure C9.07: The world's first supersonic passenger jet, Concorde, was built out of an alloy containing over 90% aluminium.

Uses of copper

Copper has a distinctive colour and is one of the least reactive metals in common use. It is used for water pipes and as roofing for buildings. Copper roofs, and indeed statues, become coated with a green layer of basic copper(II) carbonate, known as verdigris, when exposed to the atmosphere for a long time.

Copper has a very high electrical conductivity and is very ductile, and so can be easily drawn out as wire. A major use of copper is in electrical cables and domestic wiring (Figure C9.08). It is also used in the circuit boards of smartphones and other electronic equipment. The copper used for wiring and circuit boards must be of high purity (99.99%) or the electrical conductivity will be reduced significantly. This is why copper is refined to very high purity by electrolysis.

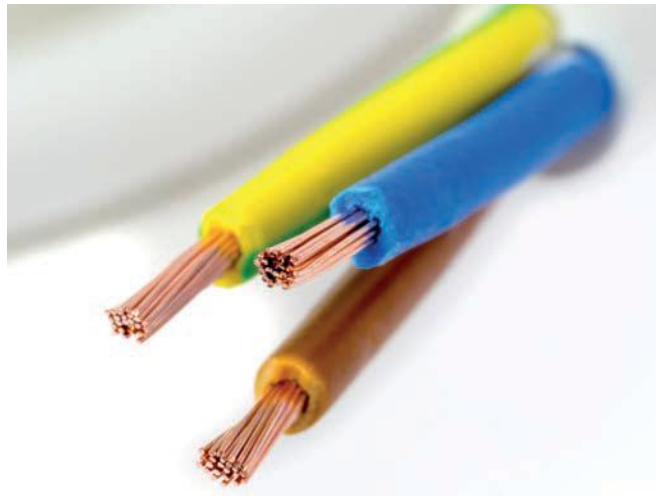

Figure C9.08: A major use for copper is in electrical cabling and domestic wiring.

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C9.03 Alloys and their properties

The Periodic Table does not list substances such as steel, bronze and brass, which in everyday use we call metals, and which share the properties listed for metals. They are not elements. They are alloys, mixtures of elements (usually metals) designed to have properties that are useful for a particular purpose.

Properties and uses of alloys

Pure metals are not always the most useful for practical purposes. Iron is quite soft and rusts easily, and copper is not very strong. However, we can modify the properties of a metal to make it harder, stronger or more resistant to corrosion by making an alloy of it. Alloys are formed by mixing the molten metals together thoroughly and then allowing them to cool and form a solid.

Ironbridge may have seen the construction of the first iron bridge, but modern bridges are now made of steel. Here, iron is alloyed with other transition elements, such as chromium and nickel, and carbon to make it stronger. The strength of steel means that more visually pleasing and longer designs are structurally possible (Figure C9.09). Other examples of alloys and their properties are given in Table C9.03.

Figure C9.09: The Chaotianmen Bridge over the Yangtze River in Chongqing City, China. The bridge is one of the world's longest through-arch steel bridges and has a span of 552 m.

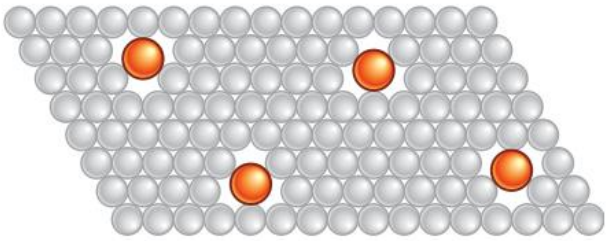
Iron, which rusts when in contact with oxygen and water, can be prevented from doing so when alloyed with chromium and nickel to make **stainless steel**.
The transition metals chromium and nickel are similar to aluminium in that they form a protective oxide layer on their surface and so are resistant to corrosion. The presence of these atoms in the alloy gives the stainless steel a resistance to rusting (Table C9.03). Iron can also be made stronger by adding carbon, forming mild steel.

Alloy	Typical composition		Particular properties and uses
brass	copper	70%	harder than pure copper; 'gold' coloured/musical instruments, ornaments, electrical connections
	zinc	30%	
bronze	copper	90%	harder than pure copper/statues, bells, machine parts
	tin	10%	
mild steel	iron	99.7%	stronger and harder than pure iron/car bodies
	carbon	0.3%	
stainless steel	iron	74%	harder than pure iron; does not rust/cutlery, surgical instruments, reaction vessels in the chemical industry
	chromium	18%	
	nickel	8%	
	Carbon	<1%	
solder	tin	50%	lower melting point than either tin or lead/making electrical connections
	lead	50%	

Table C9.03: Some important alloys and their uses.

Structure of alloys

Pure metals consist of regular layers of metal atoms. Alloys contain atoms of different types distributed throughout the structure (Figure C9.10).



An alloy

Figure C9.10: An alloy is not a mixture of metal crystal regions but a regular lattice of atoms.

The atoms in the alloy are often a different size.
This changes the properties of the metal by affecting how easily the layers can slide over each other.

KEY WORDS

stainless steel: an alloy of iron that resists corrosion; this steel contains a significant proportion of chromium which results in the alloy being resistant to rusting.

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Figure C9.11 shows how the presence of the 'impurity' atoms (the larger atoms in this diagram) makes it more difficult for the metal atoms to slide over each other. This makes the alloy harder and stronger but more brittle than the metals it is made from.

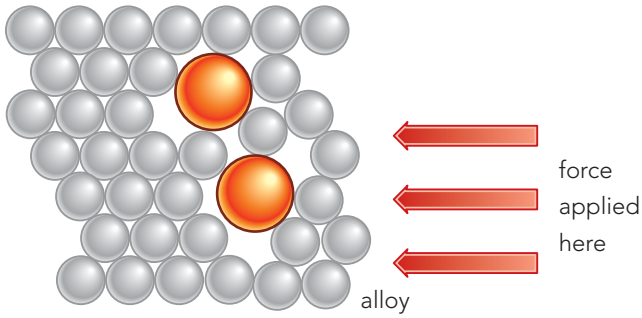

Figure C9.11: Alloys are harder and stronger than pure metals because the layers cannot slide over each other as easily as in a pure metal.

The alloy lattice is still held together by metallic bonding with delocalised electrons free to move between the layers of the structure. Alloys, therefore, share the same characteristic physical properties – electrical and thermal conductivity – as the metallic elements.

Questions

C9.07 **a** The wiring and connections involved in a domestic electric circuit must be very safe. Figure C9.12 shows the structure of a simple domestic electric plug.

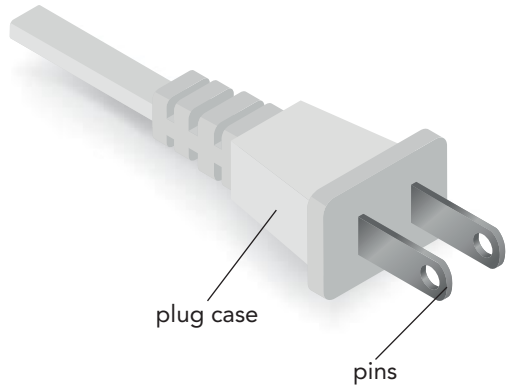

Figure C9.12: An electric plug.

The properties of four materials, some of which could be used in the home, are shown in Table C9.04.

Material	Melting point / °C	Electrical conductivity when solid
W	−39	good
X	−20 to −10	poor
Y	170 to 220	poor
Z	1083	good

Table C9.04: The properties of some materials.

Which of these materials are most suitable to make the case and pins of the electric plug (Figure C9.12). Choose *one* of the alternatives A–D (Table C9.05):

	Case	Pins
A	X	Y
B	W	X
C	Z	Y
D	Y	Z

Table C9.05: Some materials options for making a plug.

b Which alloy is most often used for the pins of such a plug?

C8.08 Stainless steel is an alloy often used to make cutlery.

a Name *two* of the main metal elements in stainless steel.

b What are *two* of the properties of stainless steel that make it particularly useful in cutlery?

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ACTIVITY C9.01

Intriguing alloys!

Alloys are metals designed for a purpose. The properties of the alloy improve on those of the parent metals. By adjusting the composition of the mixture, the properties best suited to a particular purpose are achieved.

If samples of alloys are available in your laboratory, then do examine them. Figure C9.13 shows examples of some of the more important alloys.

Figure C9.13: Some more important alloys in use (top) pewter, solder; (middle) brass, stainless steel; (bottom) mild steel, copper-nickel alloy.

In groups, discuss the different alloys in the photos and their different uses. You may want to search the internet to help you. If you have samples of the alloys available, pass these around your group as you discuss.

In your discussion, focus on:

- the composition of these different alloys
- the property that is being improved, or designed for, in each case
- the uses that these alloys are designed for.

Draw up a table of your findings to share with other groups. Follow the example shown:

Name of alloy	Composition	Properties	What could this be used for?
brass	brass is composed of …		

When considering the uses of brass and stainless steel, in particular, think about the following:

- Why is brass not used in electrical wiring?
- Why is stainless steel not used to build very large structures such as bridges?

Peer assessment

Ask your partner the following questions:

- What did I do well during our discussion about the different alloys?
- What is one thing I could improve on?

C9.04 Reactivity series

We have seen in our discussion of Group I of the Periodic Table how reactivity changes in a particular group. We also referred to the fact that the transition metals are less reactive than the metals in Groups I and II. Many of the important metals that we use in different ways come from more than one group. So, the question arises as to whether there is a broader order of reactivity (a **reactivity series**), which includes all the metals.

We will now establish the reactivity series for metals, looking at the reactions with water and dilute acid.

We will then look at metal displacement reactions that allow us to place metals precisely in a series and consider the reasons for the order we observe.

KEY WORDS

reactivity series: an order of reactivity, giving the most reactive metal first, based on results from a range of experiments involving metals reacting with oxygen, water, dilute hydrochloric acid and metal salt solutions.

Establishing the basis of a reactivity series

In reality, a range of reactivity exists for the metals. This range can be observed by simply considering the reaction of metals with air and water. The Group I metals are the most reactive of all the metals and must be kept under oil to avoid reaction with moist air. The trend within any metallic group is for reactivity to increase going down the group.

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Reactions with water

All the alkali metals react spontaneously with water to produce hydrogen gas and the metal hydroxide (Table C9.06). The reactions are exothermic. If water is dripped onto a small sample of the metal, the heat produced ignites the hydrogen gas (Figure C9.14). For sodium the flame colour is yellow.

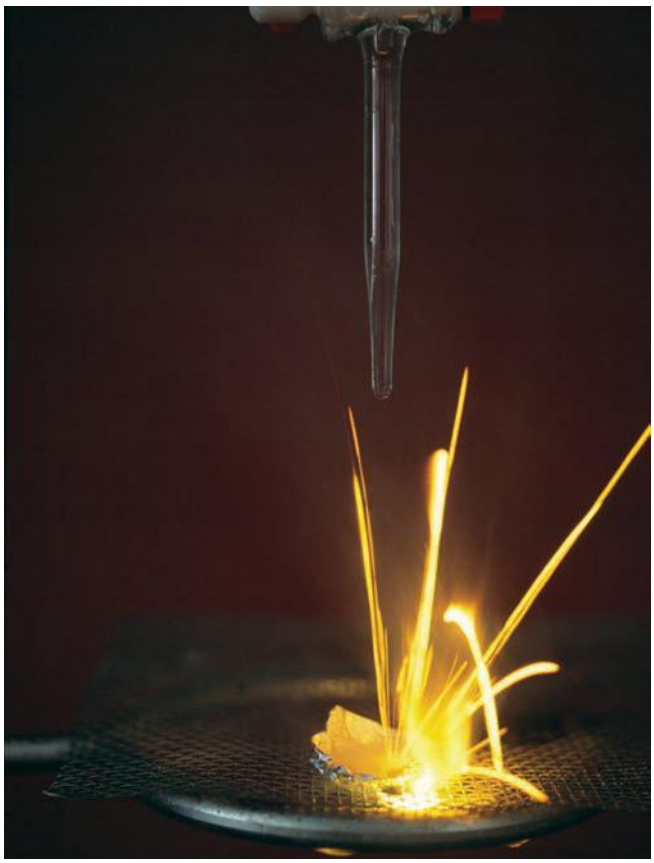

Figure C9.14: Reaction of sodium with water.

If a piece of sodium (or potassium) is placed on the surface of water in a dish, the heat produced is sufficient to melt the sodium (or potassium) as it skips over the surface of the water (Figure C9.15).

The reaction with water is the same in each case and Table C9.06 summarises the order of reactivity for Group I.

Element	Reaction with water		
lithium	reacts steadily $2Li + 2H_2O \rightarrow 2LiOH + H_2$	increasing activity	↓
sodium	reacts strongly $2Na + 2H_2O \rightarrow 2NaOH + H_2$		
potassium	reacts violently $2K + 2H_2O \rightarrow 2KOH + H_2$		

Table C9.06: Reactions of Group I metals with air and water.

Group II metals show similar trends in reactivity to Group I. However, they are less reactive than the metals in Group I. Again, reactivity increases going down the group. Magnesium reacts very slowly indeed when placed in cold water. Bubbles of hydrogen form very slowly on the magnesium ribbon. A much stronger reaction is obtained if steam is passed over heated magnesium (Figure C9.16). The magnesium glows brightly to form hydrogen and magnesium oxide:

magnesium	+	steam	→	magnesium oxide	+	hydrogen
$Mg(s)$	+	$H_2O(g)$	→	$MgO(s)$	+	$H_2(g)$

Figure C9.15: Sodium floats in a ball on the surface of water as it reacts. The change in the colour of the indicator solution shows the solution produced is alkaline.

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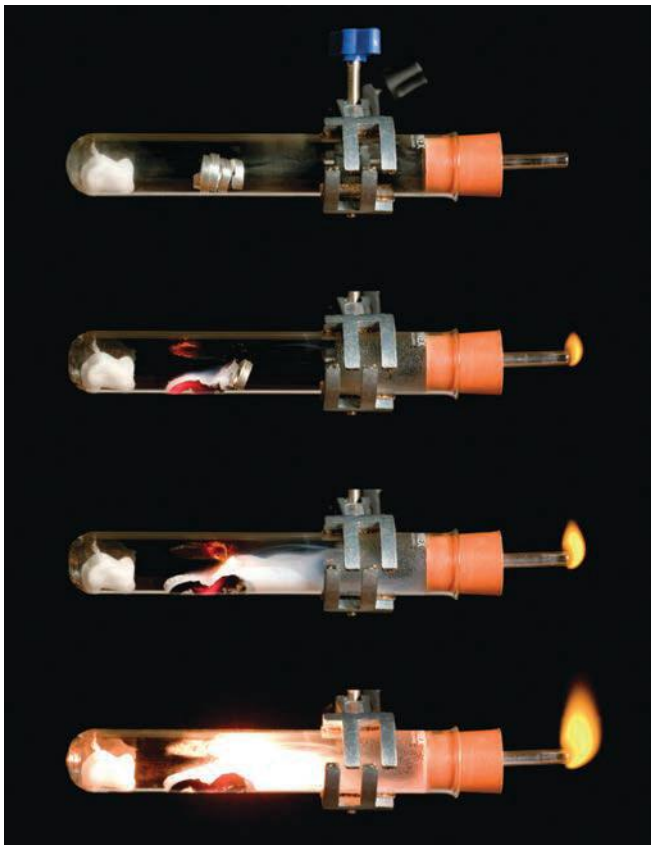

Figure C9.16: Sequence of the reaction between steam and heated magnesium.

Calcium, however, reacts strongly with cold water, giving off hydrogen rapidly:

calcium + water → calcium hydroxide + hydrogen

$$Ca(s) + 2H_2O(l) \rightarrow Ca(OH)_2(aq) + H_2(g)$$

As we have seen earlier, moderately reactive transition elements such as zinc and iron will also react with steam in a similar way to magnesium. Other transition metals such as copper, silver and gold do not react with either water or steam. Based on the reactions we have seen so far, we can put the metals considered into an order of reactivity:

potassium calcium zinc copper gold

most reactive → **least reactive**

sodium magnesium iron silver

Reactions with dilute acids

The alkali metals of Group I, and indeed calcium, are too reactive to safely add to even dilute acids in the school laboratory. They do produce hydrogen but too vigorously. Other metals show a range of reactivity with dilute acid and this is summarised in Table C9.07.

You will note from Table C9.07 that the reaction of the metal and the acid always produces a salt and hydrogen gas.

metal + acid → a metal salt + hydrogen

The reactions of the metals with dilute acids that can be carried out safely confirm the order of reactivity seen with water/steam.

magnesium iron silver

most reactive → **least reactive**

zinc copper gold

From Table C9.07, you will see that aluminium reacts less strongly than would be expected. This occurs because aluminium reacts easily with oxygen in the air to form a thin layer of aluminium oxide (Al_2O_3) that extends over the whole metal surface.

$$4Al(s) + 3O_2(g) \rightarrow 2Al_2O_3(s)$$

Metal	Observations with dilute HCl(aq) or dilute H_2SO_4(aq)	Equations
magnesium	strong reaction, bubbles of gas, magnesium disappears, colourless solution formed	$Mg(s) + 2HCl(aq) \rightarrow MgCl_2(aq) + H_2(g)$ $Mg(s) + H_2SO_4(aq) \rightarrow MgSO_4(aq) + H_2(g)$
aluminium	slow to react in cold, but bubbles form on heating, aluminium disappears, colourless solution formed	$2Al(s) + 6HCl(aq) \rightarrow 2AlCl_3(aq) + 3H_2(g)$ $2Al(s) + 3H_2SO_4(aq) \rightarrow Al_2(SO_4)_3(aq) + 3H_2(g)$
zinc	bubbles of gas, zinc disappears, colourless solution formed	$Zn(s) + 2HCl(aq) \rightarrow ZnCl_2(aq) + H_2(g)$ $Zn(s) + H_2SO_4(aq) \rightarrow ZnSO_4(aq) + H_2(g)$
iron	bubbles of gas, iron disappears, pale-green solution formed	$Fe(s) + 2HCl(aq) \rightarrow FeCl_2(aq) + H_2(g)$ $Fe(s) + H_2SO_4(aq) \rightarrow FeSO_4(aq) + H_2(g)$
copper	no reaction	
silver	no reaction	
gold	no reaction	

Table C9.07: Reactions of metals with dilute acids.

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This unreactive oxide layer is very firmly attached to the metal and does not flake off. The layer acts as a protective coating, slowing the reaction. Only when the oxide layer is removed is the true reactivity of aluminium observed. The reactivity of aluminium (when not covered in a layer of oxide) puts it in a position within the reactivity series just below magnesium, but above zinc (Figure C9.17).

Study of the reactions of metals with water and acids allows us to place hydrogen in the reactivity series (Figure C9.17) even though it is not a metal. This is useful as it demonstrates that metals higher in the series are more reactive than hydrogen. They can displace the gas from water or acids under appropriate conditions.

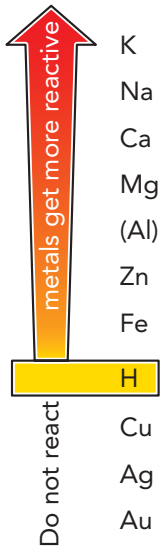

Figure C9.17: A reactivity series of metals with water and dilute acids, showing the position of hydrogen.

Questions

C9.09 Three metals, X, Y and Z, react with dilute hydrochloric acid in different ways.

Metal X: dissolves slowly with bubbles of gas given off at a slow rate.

Metal Y: dissolves very quickly and gas is produced very rapidly indeed.

Metal Z: dissolves rapidly and bubbles of gas are formed rapidly.

From these reactions, which is the order of increasing reactivity for these three metals?

A ZXY **B** YXZ

C XYZ **D** XZY

C9.10 **a** Which gas is given off when the alkali metals are reacted with water?

b Name the product, other than hydrogen, when potassium is reacted with water.

c Write a word equation for the reaction of sodium with water.

d Write a balanced chemical equation for the reaction of potassium with water.

C9.11 **a** Give *two* characteristic properties of aluminium that make it very useful for construction.

b Why does aluminium not corrode like some other metals, such as iron?

c Select from this list a metal that will not react with hydrochloric acid to produce hydrogen.

magnesium iron copper

ACTIVITY C9.02

Mind-mapping the reactivity series

The development of the metal reactivity series draws information from several different types of experiment. In your groups, you should think of the different reactions that provided evidence for the series.

Construct a mind map to show how the different areas lead from the central idea of reactivity.

Figure C9.18 shows a possible starting structure to the map.

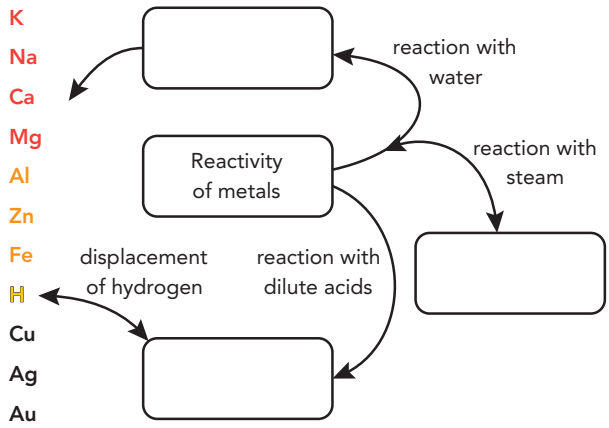

Figure C9.18: A possible framework for a mind map on the reactivity of metals.

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Copy the framework shown and use the spaces between the arrows, and alongside them, to fit in information. Use:

- equations
- lists
- comments to increase the usefulness of the information on the map.

Discuss how to improve the mind map by devising your own map of the connected ideas. Try to give your map an interesting design and present them to the class as part of a discussion of this important concept.

REFLECTION

This chapter discusses how the metal reactivity series is formed by considering the reactivity of metals with air and water. Some of these reactions are not safe to perform in a school laboratory. Do you find images and photographs of experiments useful?

Metal displacement reactions

A displacement reaction can help us to place particular metals more precisely in the reactivity series. We can use this type of reaction to compare directly the reactivity of two metals. In a displacement reaction, a more reactive metal displaces a less reactive metal from solutions of salts of the less reactive metal. This is because the more reactive metal has a greater tendency to form positive ions.

In this type of reaction, the two metals are in direct 'competition'. If a piece of zinc is left to stand in a solution of copper(II) sulfate, a reaction occurs:

$$\text{zinc} + \text{copper(II) sulfate} \rightarrow \text{zinc sulfate} + \text{copper}$$

$$Zn(s) + CuSO_4(aq) \rightarrow ZnSO_4(aq) + Cu(s)$$

grey blue colourless red–brown

The observed effect of the reaction is that the zinc metal becomes coated with a red–brown layer of copper. The blue colour of the solution fades. The solution will eventually become colourless zinc sulfate (Figure C9.19). Zinc displaces copper from solution, so zinc is more reactive than copper.

The reverse reaction does not happen. A piece of copper does not react with zinc sulfate solution.

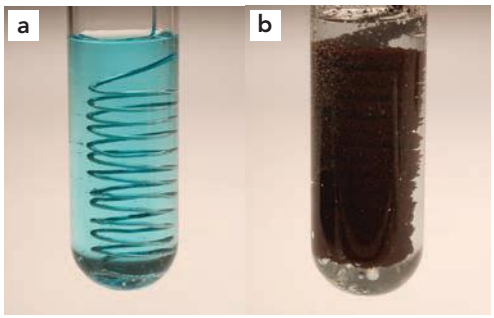

Figure C9.19 a: a piece of zinc wire is placed in copper (II) sulfate solution. **b:** After some time, the zinc has displaced the copper, forming zinc sulfate solution (colourless) and copper metal.

Although copper is an unreactive metal when tested in various ways, there are some metals that are even less reactive. Silver is a metal that is less reactive than copper. If copper metal is placed in a solution of silver nitrate, then a reaction does occur. A deposit of silver grows on the surface of the copper. The solution becomes blue because of the formation of copper nitrate solution:

$$2AgNO_3(aq) + Cu(s) \rightarrow Cu(NO_3)_2(aq) + 2Ag(s)$$

Copper displaces silver from solution, so copper is more reactive than silver. This reaction has been used to produce the 'silver pine tree' by using silver nitrate on a strip of copper folded in the shape of a tree (Figure C9.20).

Figure C9.20: A silver pine tree produced by a displacement reaction.

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In any combination, the more reactive metal is the one that can lose electrons most easily. Reactive metals are those that most readily form positive ions. This means we can make predictions using the reactivity series:

- Magnesium will displace zinc, iron, copper and silver.
- Zinc will displace iron, copper and silver.
- Iron will displace copper and silver.
- Copper will displace silver.

EXPERIMENTAL SKILLS C9.01

Displacement reactions of metals

In this experiment, you will look at the reactions between metals and solutions of their salts. You will investigate the relationship between the difference in reactivity of the metals involved and how exothermic the reaction is.

You will need:

- three boiling tubes
- measuring cylinder (10 cm^3 or 25 cm^3)
- test-tube rack
- spatula
- zinc sulfate solution (0.5 mol/dm^3)
- copper sulfate solution (0.5 mol/dm^3)
- magnesium powder
- zinc powder
- iron powder
- stopclock
- stirring thermometer (−10 to 100 °C).

Safety

Wear eye protection throughout. Be careful with chemicals. Never ingest them and always wash your hands after handling them.

Getting started

Read through the method for this experiment and create a table in which to record your results. What will you need to record?

What is a line of best fit? Working in pairs, discuss how you would draw a line of best fit.

Method

1 Using a measuring cylinder, pour 10 cm^3 of zinc sulfate solution into a boiling tube.

2 Place the tube in a rack and, using a stirring thermometer, record the temperature of the solution.

CONTINUED: C9.01

3 Add one spatula measure of magnesium powder to the tube, start the stopclock and stir the mixture.

4 Record the temperature every 30 seconds for five minutes, stirring between each reading.

5 Using a fresh tube, repeat the experiment using copper sulfate solution and zinc powder.

6 Again, record the temperature change over five minutes.

7 Repeat the experiment again, this time using copper sulfate solution and iron powder.

8 Plot three graphs on the same grid showing the temperature change over time for each metal. Draw a line of best fit on each of the three graphs.

Questions

1 What would you expect to happen if the experiment was carried out using iron(II) sulfate solution and zinc powder? Explain your answer.

2 How could you improve the accuracy of your experiment?

Peer assessment

Discuss with your partner how well you worked together during the experiment. What do you think went well? What do you think you could do better if you were asked to repeat the experiment?

Questions

C9.12 Write a word equation for the reaction between magnesium and copper(II) sulfate solution.

C9.13 State *two* observations you would see when a piece of magnesium ribbon is placed in copper(II) sulfate solution.

C9.14 Write a balanced chemical equation and an ionic equation for the reaction between magnesium and copper(II) sulfate solution.

C9.15 We have a list of metals in a particular order in the reactivity series. Can you work out a memory aid (mnemonic) to help remember the order?

C9.05 Corrosion of metals

The problem of corrosion

When a metal is attacked by air, water or other surrounding substances, it is said to corrode. Most metals corrode. They undergo a chemical reaction with oxygen and other gases in the air to form compounds that collect on the surface of

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the metal. Some very reactive metals such as sodium and potassium need to be stored under oil to keep them away from air and water. Others, such as calcium, will slowly corrode away to powder over time.

In the case of iron and steel, the corrosion process is also known as **rusting**. Rusting is a serious economic problem. Large sums of money are spent each year replacing damaged iron and steel structures or protecting structures from such damage. Rust is a red–brown powder consisting mainly of hydrated iron(III) oxide ($Fe_2O_3 \cdot H_2O$). Water and oxygen are essential for iron to rust (Figure C9.21). The problem is made worse by the presence of salt; seawater increases the rate of corrosion as can be seen on countless shipwrecks around the world (Figure C9.21). Acid rain also increases the rate at which iron objects rust.

Figure C9.21: Rusted shipwreck on rocky beach.

KEY WORD

rusting: the corrosion of iron and steel to form rust (hydrated iron(III) oxide).

Aluminium is more reactive than iron, but it does not corrode in the damaging way that iron does. Both metals react with air. In the case of aluminium, a very thin single layer of aluminium oxide forms, which sticks strongly to the surface of the metal. This micro-layer seals the metal surface and protects it from further attack. Aluminium is a useful construction material because it is protected by this layer. The protective layer of aluminium oxide can be made thicker by electrolysis (anodised aluminium).

In contrast, when iron corrodes, the rust forms in flakes. It does not form a single layer. The attack on the metal can continue over time as the rust flakes come off, and holes can be formed in iron sheets by the rusting process. Chromium is another metal, similar to aluminium, that is protected by an oxide layer. If chromium is alloyed with iron, a 'stainless' steel is produced. However, it would be too expensive to use stainless steel for all the objects built out of iron.

Rust prevention

Many methods have been devised to protect iron and steel from rusting.

Barrier methods

Rust can be prevented by a coating of material that prevents the iron or steel from coming into contact with water and oxygen. These methods are known as barrier methods.

Painting

Painting is a very common method of protection, and is used for objects ranging in size from ships and bridges to garden gates. Some paints react with the metal to form a stronger protective layer. However, generally, painting only protects the metal for as long as the paint layer is unscratched. Regular repainting is often necessary to keep this protection intact.

Oiling and greasing

The oiling and/or greasing of the moving parts of machinery forms a protective film, preventing rusting. Again, the treatment must be repeated to continue the protection.

Plastic coatings

Plastic coatings are used to form a protective layer on items such as refrigerators and garden chairs. The plastic poly(vinyl chloride), PVC, is often used for this purpose.

ACTIVITY C9.03

Causes of rusting

The results of an experiment to investigate rusting are shown in Figure C9.22. The following tasks are based on the experiment. Discuss each of them with a partner before you attempt to write anything down.

- What *three* things do the results of this experiment tell you about rusting?
- Make a list of the apparatus you would need to carry out this experiment.
- Write an instruction sheet, explaining to someone else how they should carry out the experiment.
- Think of a possible fifth tube you could set up to show a way of preventing rusting.

Discuss your answers with a partner and comment on how each of you completed the task. Were you able to evaluate the different causes clearly?

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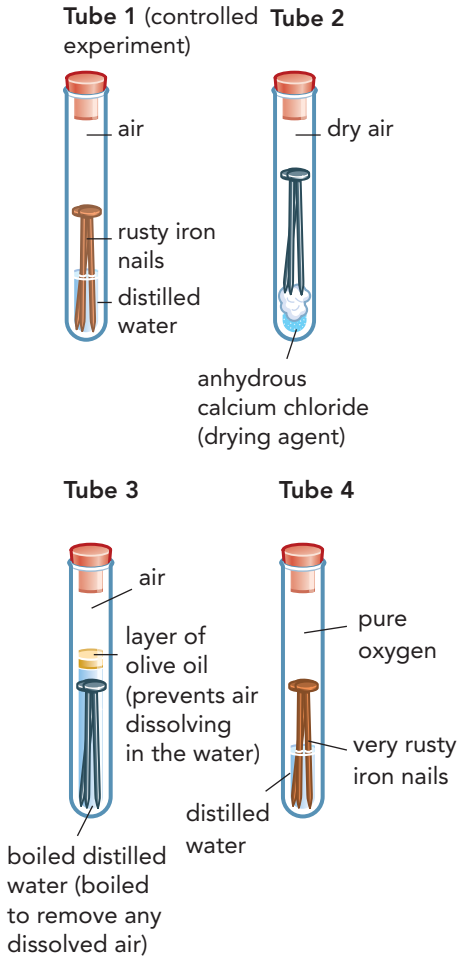

Figure C9.22: The results of an experiment to investigate the factors that are involved in rusting. In tube 2, the air is dry, so the nails do not rust. In tube 3, there is no oxygen in the water, so the nails do not rust. In tube 4, pure oxygen and water are present, so the nails are very rusty.

Galvanising and sacrificial protection

With any methods of barrier protection, there is an issue. If the barrier is damaged, the metal underneath will corrode. As a solution to this, an object may be coated with a layer of the more reactive metal, zinc. This is called **galvanising**. It has the advantage over other barrier methods in that the protection still works even if the zinc layer is badly scratched. Galvanising is, in fact, both a barrier method of protection, while the zinc layer is unbroken, and a form of sacrificial protection (see below), if the zinc layer is scratched or broken. If the zinc layer is broken it is still corroded away in preference to the iron as zinc is a more reactive metal than iron.

The zinc layer (Figure C9.23) can be applied by several different methods. These include electroplating or dipping the object into molten zinc. The bodies of cars are dipped into a bath of molten zinc to form a protective layer.

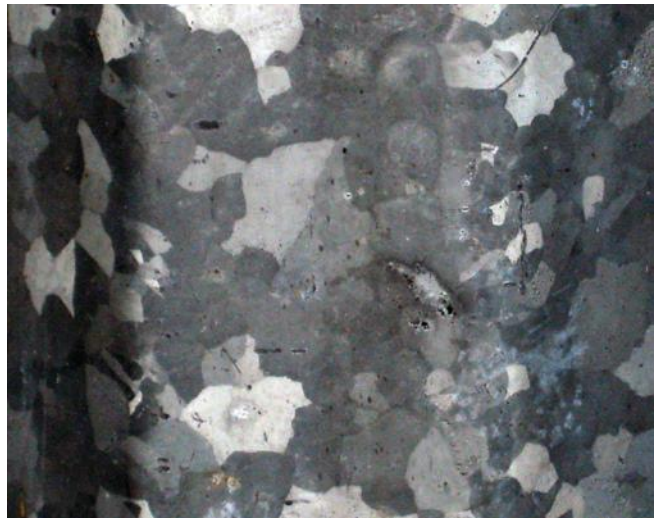

Figure C9.23: A photograph of zinc grains on a galvanised fence post.

Sacrificial protection is a method of rust prevention in which blocks of a reactive metal are attached to the iron surface. Zinc or magnesium blocks are attached to oil rigs and to the hulls of ships (Figure C9.24). These metals are more reactive than iron and will be corroded in preference to it: they 'sacrifice' themselves so the iron does not rust. Underground gas and water pipes are connected by wire to blocks of magnesium to obtain the same protection. In all cases, an electrochemical cell is set up. The metal blocks lose electrons in preference to the iron and so prevent the iron from forming iron(III) oxide. The more reactive metal oxidises more readily than iron, so it 'sacrifices' itself while the iron does not rust.

KEY WORDS

galvanising: the protection of iron and steel objects by coating with a layer of zinc.

sacrificial protection: a method of rust protection involving the attachment of blocks of a metal more reactive than iron to a structure; this metal is corroded rather than the iron or steel structure.

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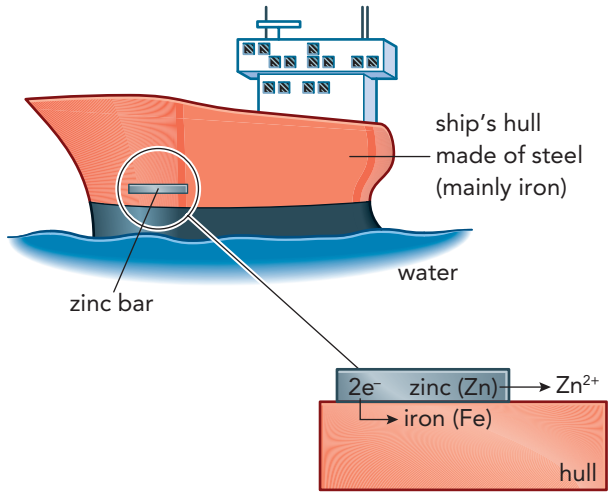

Figure C9.24: Blocks of zinc (or magnesium) are used for the sacrificial protection of the hulls of ships.

Questions

C9.16 What *two* substances must be present before iron can rust? What other factors can increase the rate of rusting?

C9.17 What simple barrier methods can be used to prevent rusting?

C9.18 Steel is often plated with another metal. Chromium and zinc are both used. Suggest why zinc is more effective at stopping rusting.

C9.06 Extraction of metals

Some metals exist as pure metals in nature. Others are very difficult to extract from their compounds contained in **ores**. Those metals that do not occur uncombined (native) in the ground can usually be found as the metal oxide, or a compound that can easily be converted to the oxide. To extract the metal from this oxide we need to carry out a reduction (the removal of the oxygen from the metal).

KEY WORD

ore: a naturally occurring mineral from which a metal can be extracted.

We have established that there is a reactivity series based on the differences in reactivity of the various metals. The most reactive metals are those that combine most strongly in their compounds or form positive ions most easily. We placed hydrogen in that reactivity series because it is useful to know its reactivity relative to the different metals. We found that hydrogen is less reactive than zinc, but more reactive than copper, for instance. Hydrogen will reduce (remove oxygen from) copper oxide to copper metal (Chapter C6); but hydrogen will not reduce zinc oxide to zinc.

It would also be useful to place carbon in the reactivity series as it is a strong reducing agent providing a very useful method of extracting metals. Practical experiments have shown that carbon is between aluminium and zinc in the series (Figure C9.25).

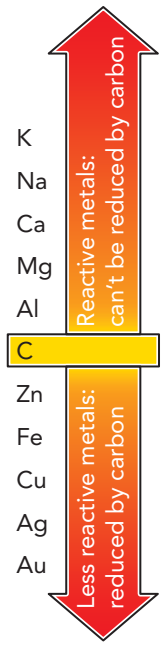

Figure C9.25: Position of carbon in the reactivity series.

Metals below carbon in the series can be extracted by heating their oxides with carbon (although a number of these are found in nature uncombined), but those above carbon must be extracted by electrolysis. If a metal is below carbon in the reactivity series the oxygen in its oxide will form bonds more easily with carbon rather than remain as the metal oxide.

If the metal is more reactive than carbon, then reduction must be achieved by the reaction that takes place at the cathode during electrolysis. The metal ions in the oxide must gain electrons to produce the free metal. This is the type of reaction that takes place in the electrolytic extraction of aluminium from bauxite.

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EXPERIMENTAL SKILLS C9.02

Carbon as a reducing agent in metal extraction

In this experiment, you will heat copper(II) oxide with carbon to see whether reduction takes place. If the copper(II) oxide is reduced to copper then it helps place carbon in the reactivity series.

You will need:

- test-tube
- test-tube holder
- test-tube rack
- spatula
- Bunsen burner
- heat-resistant mat
- powdered charcoal
- copper oxide.

Safety

Wear eye protection throughout. Point the test-tube away from you and others while heating it. Be careful with chemicals. Never ingest them and always wash your hands after handling them.

Getting started

You will need the roaring blue flame from the Bunsen burner produced when the air hole is fully open. Practise producing this flame prior to the experiment. When heating the tube, you will need to hold the end of the tube just above the blue cone in the flame.

Method

1. Place one spatula measure of copper oxide into the test-tube.
2. Add one spatula measure of powdered charcoal. DO NOT mix the two.
3. Set up the Bunsen burner on the heat-resistant mat.
4. Place the test-tube in the test-tube holder and heat the two layers strongly for five minutes with the Bunsen burner.
5. Allow the test-tube to cool in the test-tube rack.
6. Look closely at the point where the two powders join.

Questions

1. What do you see at the place where the two powders join?
2. Write an equation for the reaction that is occurring.

Self assessment

Was your experiment successful? How do you know?

Think about how you did each of the steps in the method. If you were to do this experiment again, is there anything you would do differently?

Extraction of iron from its ore

Iron is the second most common metal in the Earth's crust. The main ore of iron is **hematite** (Fe_2O_3). This ore is rich in iron, containing more than 60% iron.

The iron is obtained by reduction with carbon in a **blast furnace** (Figure C9.26).

Production of iron in the blast furnace

The blast furnace is a steel tower about 30 metres high. It is lined with refractory (heat-resistant) bricks of magnesium oxide that are cooled by water. The furnace is loaded with the 'charge' of raw materials, which consists of iron ore, coke (a form of carbon made from coal) and

Figure C9.26: A worker in protective clothing takes a sample from a blast furnace in a steel works.

KEY WORDS

hematite: the major ore of iron, iron(III) oxide.

blast furnace: a furnace for extracting metals (particularly iron) by reduction with carbon that uses hot air blasted in at the base of the furnace to raise the temperature.

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limestone (a **mineral** form of calcium carbonate). The charge is sintered (the ore is powdered and heated with coke and limestone) to make sure the solids mix well, and it is mixed with more coke. Blasts of hot air are sent into the furnace through holes near the bottom of the furnace. A series of chemical reactions takes place within the furnace to produce molten iron.

The carbon (coke) burns in the air blast and the furnace gets very hot from the heat from this exothermic reaction.

carbon + oxygen → carbon dioxide

As carbon dioxide rises through the furnace it reacts with more carbon and is reduced to carbon monoxide.

carbon dioxide + carbon → carbon monoxide

The most important reaction that then occurs is the reduction of the ore by carbon monoxide:

iron(III) oxide + carbon monoxide → iron + carbon dioxide

The iron produced flows to the bottom of the furnace where it can be 'tapped off' as a liquid because the temperature at the bottom of the furnace is higher than the melting point of iron (Figure C9.27).

One of the major impurities in iron ore is sand (silicon(IV) oxide, SiO_2 – also called silica). The limestone added to the furnace helps to remove this impurity. The limestone (calcium carbonate) undergoes a thermal decomposition reaction in the furnace to produce calcium oxide and carbon dioxide.

calcium carbonate → calcium oxide + carbon dioxide

The lime produced then reacts with the silica to form calcium silicate **slag**.

calcium oxide + silicon(IV) oxide → calcium silicate

KEY WORDS

limestone: a form of calcium carbonate ($CaCO_3$).

mineral: a naturally occurring rock containing a particular compound.

slag: a molten mixture of impurities, mainly calcium silicate, formed in the blast furnace.

The calcium silicate formed is also molten. It flows down the furnace and forms a molten layer of slag on top of the iron (Figure C9.27). It does not mix with the iron, and it is less dense. The molten slag is 'tapped off' separately. When solidified, the slag is used in concrete for buildings and road surfacing.

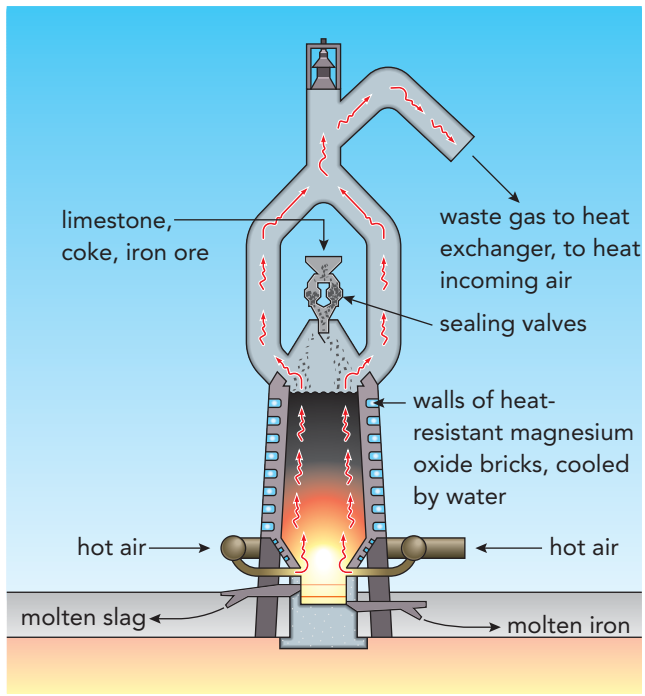

Figure C9.27: Reduction of iron ore to iron in the blast furnace.

The hot waste gases escape from the top of the furnace. The gases are used in heat exchangers to transfer heat to the incoming air. This helps to reduce the energy costs of the process. The extraction of iron is a continuous process. It is much cheaper than the electrolytic processes used to extract other metals.

The key features of the blast furnace extraction of iron from iron ore (hematite) are:

- the burning of carbon (coke) to provide heat and produce carbon dioxide
- the reduction of carbon dioxide to carbon monoxide
- the reduction of iron(III) oxide by carbon monoxide
- the thermal decomposition of limestone (calcium carbonate) to produce calcium oxide (lime)
- the use of limestone to remove the main impurity (sand) as slag (calcium silicate).

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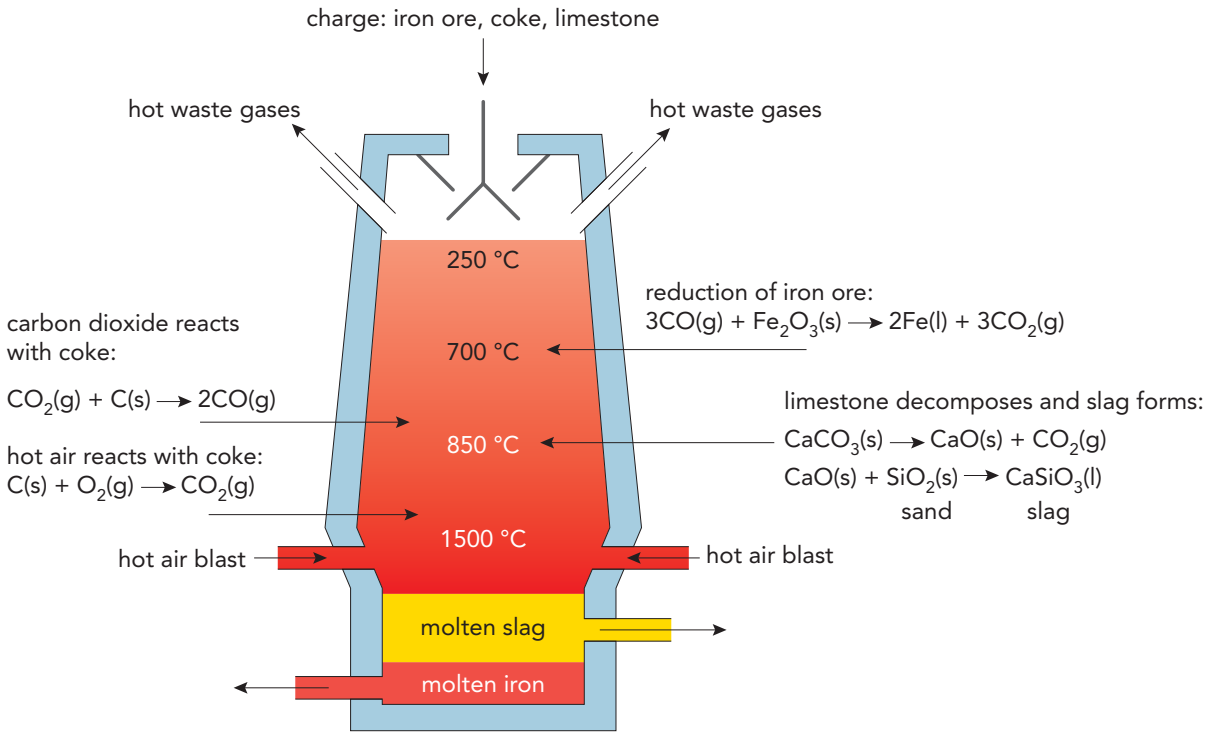

Figure C9.28: Key reactions of the extraction of iron and the regions of the blast furnace where they take place.

Chemistry of the blast furnace

A number of different reactions take place in the blast furnace. The reaction that takes place depends on the position in the furnace and the temperature. Figure C9.28 shows the regions of the furnace where the key reactions take place and the chemical equations for those reactions.

The iron produced in the blast furnace is only about 95% pure. The impurities are mainly carbon, but they also include sulfur, silicon and phosphorus. Most of the iron produced in the furnace is taken and purified further and then turned into various forms of steel.

Questions

C9.19 Why is limestone added to the blast furnace? Write the balanced symbol equation for the thermal decomposition of the limestone to lime.

C9.20 What is the reducing agent in the extraction of iron from iron(III) oxide? Give the word equation and the balanced symbol equation of the reduction reaction.

C9.21 Write the word and symbol equations for the production of the calcium silicate slag.

REFLECTION

What features helped you understand why different methods of extraction are used for different metals? Do you think you learnt more from the written text or from the figures? Would a video help you to understand this topic further?

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PROJECT C9.01 UNDERSTANDING REDOX AND THE REACTIVITY SERIES

Redox reactions are an important type of reaction in chemistry. You have met ideas on this type of reaction in both this and several earlier chapters (especially Chapter C6).

Together with a partner, write a podcast script (Figure C9.29) that describes the key features of these reactions. In your podcast script:

- Explore the word 'redox' itself. What does it stand for? Redox reactions can be seen as competitions between elements. But competitions for what?
- Discuss the different definitions of the processes involved, including:
  - removal/addition of oxygen
  - gain/loss of electrons.
- How does the idea of redox fit with the reactions used in this chapter to place the metals in a detailed reactivity series? Conclude your presentation by describing a particularly important example of this type of reaction and its significance.

Figure C9.29: Communicating ideas through a podcast.

SUMMARY

Metals and non-metals have different physical properties.
The key physical properties of metals are that they conduct electricity and heat, have high melting and boiling points, and are malleable.
Some metals are very useful. Aluminium is particularly useful because of its low density and resistance to corrosion. Copper is also very useful, due to its high conductivity.
Alloys are mixtures of metals and other elements, which are often chosen to increase the strength, hardness and usefulness of the pure metal.
Stainless steel is a hard alloy created specifically to resist corrosion. It is used to make cutlery.
Alloys can be identified in diagrams of metallic structure by noting the different sizes of the atoms in the layered arrangement shown.
Alloys are stronger and harder than pure metals as the layers in the structure can no longer slide over each other.
Metals show different levels of reactivity and can be arranged in a reactivity series. From highest reactivity to lowest: potassium, sodium, calcium, magnesium, aluminium, (carbon), zinc, iron, (hydrogen), copper, silver, gold.
The different levels of reactivity can be seen in the way the different metals react with reagents such as water and dilute acids.
Metal displacement reactions provide evidence that helps to bring detail to the reactivity series.
A more reactive metal will displace a less reactive metal from a solution of its salts.
The position of a metal in the series is related to the tendency of the metal to form its positive ion in reactions.
Rusting of iron and steel requires the presence of water and oxygen.
Rusting can be prevented by painting, greasing and coating with plastic.
Rusting can also be prevented by galvanising with zinc. The zinc both acts as a barrier and provides sacrificial protection.
Sacrificial protection uses a more reactive metal to protect a less reactive metal.
The method of extracting a metal from its ore depends on the reactivity of the metal.
The least reactive metals, such as copper, can be found uncombined in the Earth's crust.
Metals that are less reactive than carbon can be extracted by heating with carbon in a blast furnace.
Iron is extracted from hematite by reduction in a blast furnace.
We can describe the reactions in a blast furnace using word and symbol equations.
Aluminium is more reactive than carbon and must be extracted by electrolysis from its ore, bauxite.

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PRACTICE QUESTIONS

1 **Identify** which of the following statements is true for *all* metals.

A They are grey in colour.

B They are weak and brittle solids.

C They react with water.

D They may be used to make alloys with other elements. **[1]**

2 Identify which of these metals will react with cold water to produce hydrogen gas.

A copper **B** zinc **C** potassium **D** aluminium **[1]**

3 The table shows some of the properties of metals and non-metals.

Place ticks (✓) in the table to show whether each property applies to most metals, most non-metals, or both.

Property	Applies to most metals	Applies to most non-metals
they conduct electricity		
they react with oxygen in the air		
they are brittle		
they can easily be bent and shaped		
they have high melting points		

[6]

4 Aluminium is used for the following purposes: manufacturing aircraft, overhead electrical power cables and food containers.

a **State** the property of aluminium that is most important for its use in aircraft manufacture. **[1]**

b State the property that is most useful for its use in food containers. **[1]**

c Brass is also important in the home for electrical connections.

Identify the four words that can be used to describe brass.

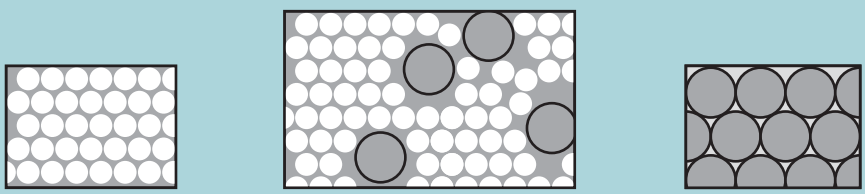
Alloy **Compound** **Conductor** **Element** **Metal** **Mixture** **[4]**

d Stainless steel is used to make cutlery.

Describe how stainless steel differs from iron. **[2]**

[Total: 8]

5 The diagram shows an alloy and the metals from which it is made.



pure metal A alloy pure metal B

COMMAND WORD

identify: name/select/recognise.

COMMAND WORDS

state: express in clear terms.

describe: state the points of a topic/give characteristics and main features.

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CONTINUED

a **Explain** why the two pure metals are malleable. [1]

b Explain why the alloy is not malleable. [1]

c **Consider** whether the alloy is able to conduct electricity. [2]

[Total: 4]

6 A student investigated the reactivity of a number of metals. First, she took a strip of zinc and dropped it into a beaker of dilute hydrochloric acid.

a Describe what the student saw as the zinc reacted. [2]

She then dropped a different strip of zinc into cold water.

b Describe what she saw. [1]

She then tried the same experiments with three other metals: calcium, iron and a third metal that she did not know the name of. The results are shown in the table.

Metal	Reaction with acid	Reaction with water
calcium	reacted violently	reacted rapidly
iron	reacted slowly	no reaction
zinc	reacted moderately	no reaction
unknown metal	reacted quite quickly	no reaction

c List the metals in increasing order of reactivity (least reactive first). [2]

d **Suggest** the name of the 'unknown metal'. [1]

e Some of these reactions produced a gas. **Give** a test for this gas.

Test: _____

Result: _____ [2]

[Total: 8]

7 A student put a strip of a silver/grey metal, A, into a test-tube containing a blue solution. The solution became paler in colour and the strip of metal was covered with a brown coating.

When the same silver metal was added to a solution of zinc sulfate, no reaction took place.

a Identify the blue solution. [1]

b Suggest the identity of metal A. [1]

In a separate experiment the student put a strip of copper into a solution of silver nitrate, $AgNO_3(aq)$.

c Give an equation including state symbols for the reaction which took place. [3]

d Suggest what observations the student would have made. [2]

e The student repeated this experiment using zinc nitrate solution.

Explain why no reaction took place. [1]

[Total: 8]

COMMAND WORDS

explain: set out purposes or reasons/make the relationships between things clear/say why and/or how and support with relevant evidence.

consider: review and respond to given information.

COMMAND WORDS

suggest: apply knowledge and understanding to situations where there is a range of valid responses in order to make proposals/put forward considerations.

give: produce an answer from a given source or recall/memory.

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CONTINUED

8 The equation shows how iron(III) oxide is reduced to form iron in the blast furnace.

iron(III) oxide(s) + carbon monoxide(g) → iron(l) + carbon dioxide(g)

a State the name of the main ore of iron containing iron(III) oxide. **[1]**

b Identify the substance that is the reducing agent in the reaction. **[1]**

c Suggest why the iron is produced as a liquid. **[1]**

d Slag is also formed in the blast furnace. Describe how slag is produced. **[2]**

[Total: 5]

9 Iron and aluminium are two of the most important metals for industry. They are both extracted from their oxides.

This reaction of carbon occurs during both extraction processes.

$$C(s) + O_2(g) \rightarrow CO_2(g)$$

a State where the oxygen comes from when this reaction occurs in the extraction of iron. **[1]**

b Give *two* reasons why this reaction is important in the extraction of iron. **[2]**

Carbon dioxide is also produced from the thermal decomposition of limestone, $CaCO_3$.

$$CaCO_3(s) \rightarrow CaO(g) + CO_2(g)$$

c Explain how the calcium oxide produced is important in the extraction of iron. **[2]**

[Total: 5]

10 When iron is left in the open air it rusts. Iron can be protected from rusting by painting or coating with oil.

Coating the iron with zinc works more effectively than these methods.

a Explain how coating with paint can protect the iron. **[2]**

b Identify the process of coating iron with zinc. **[1]**

c Suggest why this method is more effective than coating with paint. **[1]**

d If an iron object is connected to a block of a metal such as zinc or magnesium, it does not rust, even though it is exposed to air and water.

Explain how this protection works. **[3]**

[Total: 7]

SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
compare the general physical properties of metals and non-metals	C9.01			
describe the general chemical properties of metals	C9.01			

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CONTINUED

I can	See topic . . .	Needs more work	Almost there	Confident to move on
describe the uses of metals; particularly the uses of aluminium and copper	C9.02			
describe an alloy as a mixture of a metal with other elements, including brass and stainless steel	C9.03			
understand that alloys can be harder or stronger than the pure metals and therefore more useful	C9.03			
identify representations of alloys from diagrams of structure	C9.03			
describe how the properties of metals can be changed by alloying	C9.03			
understand the concept of a reactivity series	C9.04			
state the order of the reactivity series	C9.04			
describe the reactions of potassium, sodium and calcium with cold water	C9.04			
describe the reaction of magnesium with steam	C9.04			
describe the reactions of metals with dilute hydrochloric acid	C9.04			
relate the reactions of metals to their position in the reactivity series	C9.04			
deduce an order of reactivity from a set of experimental results	C9.04			
relate the reactivity series to the displacement reactions of several metals	C9.04			
state the conditions required for the rusting of iron and steel	C9.05			
describe barrier methods for rust prevention, including painting, greasing and coating with plastic	C9.05			
describe the use of galvanising with zinc as both a barrier and sacrificial protection method of rust prevention	C9.05			
explain sacrificial protection in terms of the reactivity of the metals used and the loss of electrons	C9.05			
understand how the ease of extraction of a metal from its ore is related to its position in the reactivity series of metals	C9.06			
state that the main ore of aluminium is bauxite and that aluminium is extracted from it by electrolysis	C9.06			
state that iron is extracted from hematite in the blast furnace	C9.06			
describe the chemical changes taking place in the blast furnace extraction of iron, including balanced symbol equations.	C9.06			

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C10 Chemistry of the environment

All learners study some content in this chapter

IN THIS CHAPTER YOU WILL:

- learn how to describe the composition of clean dry air
- investigate common air pollutants and their adverse effects
- describe how carbon dioxide and methane are greenhouse gases linked to global warming and climate change
- consider strategies to reduce climate change
- consider strategies to reduce the effects of acid rain
- explain how oxides of nitrogen form in car engines and are removed by catalytic converters
- understand how greenhouse gases cause global warming
- describe the tests for the presence of water, and why distilled water is used in experiments
- describe tests for the purity of water
- describe the main steps needed to purify the domestic water supply.

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BEFORE YOU START

Air and water are being contaminated with substances produced because of human activities.

In a small group, discuss the importance of clean air and water to human life. Can you think of different types of air and water pollution (contamination with other substances) in and around the area where you live or go to school?

A wide range of pollutants is generated by manufacturing industries, power plants, farms and transportation. Make a list of some of the pollutants you already know of and try to give their sources. Having done this, discuss the impact these pollutants can have on people's daily lives and whether your lifestyle choices contribute to local air and water pollution.

SCIENCE IN CONTEXT C10.01

The growing problem of air pollution

The air we breathe is a mixture of different gases. There are the non-toxic gases such as nitrogen and argon, which we simply breathe in and out. There is the oxygen we require for respiration. But there are also some gases that have been linked to health problems, quality of life and environmental issues (Figure C10.01). These pollutant gases are generally the result of human activity, with most being produced either by burning **fossil fuels** or because of modern intensive farming methods. These pollutants include oxides of nitrogen, sulfur dioxide, carbon monoxide, methane, particulates and carbon dioxide. Governments around the world are aware of the seriousness of these pollutants and are gradually working together to set strict limits on how much of the pollutants can be released into the environment.

To meet these targets and improve air quality, governments need to change in part how their citizens lead their daily lives. Steps to do this are already being made with cities banning high-polluting vehicles or setting high tariffs (congestion charges) to drive into city centres. Some governments are increasing taxes on companies or those technologies that use fossil fuels. Governments can also choose to promote more sustainable methods of farming and encourage people to eat less meat in their diets.

It is important to consider whether decisions about environmental effects should be left to governments, companies or individuals. These are difficult decisions, and many different factors have to be considered. Individuals may feel powerless to act in isolation or believe that changes in lifestyle do not have a significant impact. Companies may resist changes because of concerns over increased prices. Governments face problems as they are linked by large global trade agreements and increasing tariffs to meet a greener future in one country may simply result in increased imports from places that have less-strict environmental standards.

Figure C10.01: High levels of industrial atmospheric pollution are causing environmental problems.

Discussion questions

1 Think about how the air quality where you live compares with other parts of the world. What might be the reasons for the differences in air quality?

2 What factors might encourage or prevent an individual choosing more environmentally friendly options in their day-to-day lifestyle?

KEY WORDS

fossil fuels: fuels, such as coal, oil and natural gas, formed underground over geological periods of time from the remains of plants and animals.

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C10.01 Air quality and climate

Composition of air

The **atmosphere**, a layer approximately 480 km thick that surrounds the Earth, is made up of a mixture of air and water vapour. Levels of water vapour are highly variable and can range from 0.2% in high mountain regions to 4.0% in tropical rainforests. To compare samples of air, the water vapour is removed to produce **clean dry air**.

Clean dry air consists mainly of 78% nitrogen (N_2) and 21% oxygen (O_2) (Figure C10.02). This leaves only 1% for the other gases. Argon makes up 0.9% so the other gases are only present in very small quantities. The remainder includes carbon dioxide (CO_2), other noble gases (neon, krypton and helium), methane, oxides of nitrogen and sulfur dioxide.

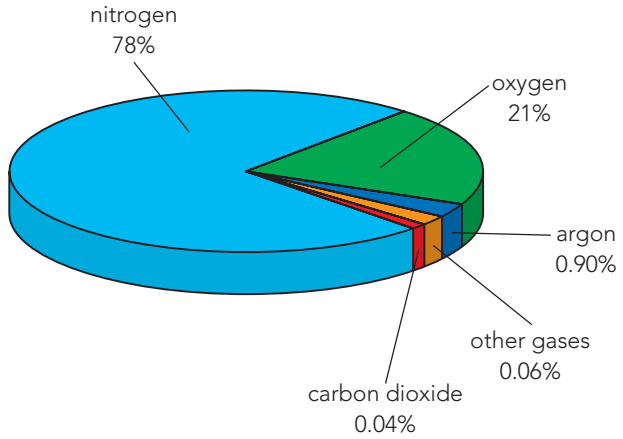

Figure C10.02: Composition of clean dry air.

Oxygen is essential for **respiration** and so life on Earth is dependent on it. We can extract oxygen from the air to treat people with respiratory problems in hospital and for industrial welding.

Nitrogen, as found in the atmosphere, is unreactive. Some species of bacteria can use ('fix') nitrogen directly from the air to produce amino acids, but most living organisms are unable to convert gaseous nitrogen into useful products. Nitrogen can also be extracted from the air and is used as an **inert** atmosphere for food packaging or combined with hydrogen to produce ammonia. Ammonia is the starting material for most fertilisers.

Carbon dioxide, although used in **photosynthesis** and produced by respiration, makes up just 0.04% of the Earth's atmosphere.

Air pollution

Human activity has contributed significantly to atmospheric pollution and increased levels of oxides of nitrogen, sulfur dioxide, methane, carbon monoxide, carbon dioxide and **particulates**. Carbon dioxide occurs naturally in the air but, when present in larger quantities, it is classed as a **pollutant** because it is partly responsible for **global warming** and the associated **climate change**. Each of these pollutants has a different effect and these are detailed below.

Sulfur dioxide

Fossil fuels such as coal and crude oil often contain sulfur as an impurity. When the fuel is burnt, the sulfur combines with oxygen from the air to release sulfur dioxide (SO_2).

$$S(s) + O_2(g) \rightarrow SO_2(g)$$

Sulfur dioxide has been linked to breathing difficulties because it irritates the lining of the respiratory tract and so is especially dangerous for people with asthma.

KEY WORDS

atmosphere: the layer of air and water vapour surrounding the Earth.

clean dry air: containing no water vapour and only the gases that are always present in the air.

respiration: the chemical reaction (a combustion reaction) by which biological cells release the energy stored in glucose for use by the cell or the body; the reaction is exothermic and produces carbon dioxide and water as the chemical by-products.

inert: a term that describes substances that do not produce a chemical reaction when another substance is added.

photosynthesis: the chemical process by which plants synthesise glucose from atmospheric carbon dioxide and water, giving off oxygen as a by-product; the energy required for the process is captured from sunlight by chlorophyll molecules in the green leaves of the plants.

particulates: very tiny solid particles produced during the combustion of fuels.

pollutants: substances, often harmful, which are added to another substance.

global warming: a long-term increase in the average temperature of the Earth's surface, which may be caused in part by human activities.

climate change: changes in weather patterns brought about by global warming.

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Sulfur dioxide, along with nitrogen oxide, is also known to react with oxygen and water vapour in the air to form **acid rain**. Acid rain is harmful to life both on land and in the water. Increased acidity levels in lakes can kill fish and other aquatic life, while many plants are extremely sensitive to pH levels. Some building materials react with acid rain over time, leading to increased rates of damage and corrosion (Figure C10.03).

Figure C10.03: Medieval sculpture damaged by acid rain.

The main sources of sulfur dioxide are electricity generation using either coal or oil and burning fossil fuels such as petrol (gasoline) and diesel in vehicle engines (Figure C10.04).

To prevent the harmful effects of sulfur dioxide, scientists have researched ways to reduce the amounts being released into the air. To prevent the formation of SO_2, it is possible to remove most of the sulfur-containing compounds before combustion. This gives the ultra low sulfur petrol and diesel which are required in most countries across the world.

Removal of SO_2 from combustion gases is done in a chimney ('flue'). The flue gases react with water to form an acidic solution that can then be neutralised by the reaction with calcium oxide in a process known as **desulfurisation** or 'scrubbing' (this is an **acid–base reaction**).

KEY WORDS

acid rain: rain that has been made more acidic than normal by the presence of dissolved pollutants such as sulfur dioxide (SO_2) and oxides of nitrogen (nitrogen oxides, NO_x).

desulfurisation: the removal of sulfur dioxide from the fumes of power stations.

acid–base reaction: a chemical reaction between an acid and a base.

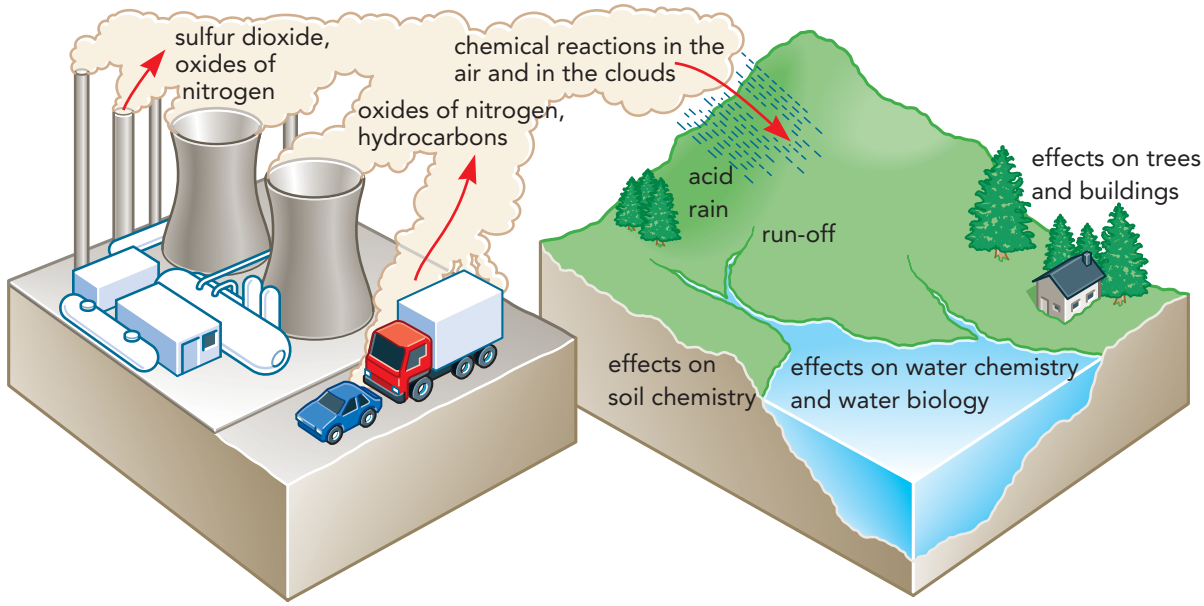

Figure C10.04: Formation of acid rain.

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Oxides of nitrogen

Oxides of nitrogen, also referred to as nitrogen oxides (NO_x), is the general name given to represent several different oxides including nitric oxide (NO) and nitrogen dioxide (NO_2). Oxides of nitrogen form when nitrogen and oxygen from the air react at high temperatures.

An example of this is:

$$N_2(g) + O_2(g) \rightarrow 2NO(g)$$

Like sulfur dioxide, oxides of nitrogen have been linked to the formation of acid rain (Figure C10.04). An example of a reaction showing how nitrogen dioxide reacts with water to form nitric acid (HNO_3) is:

$$3NO_2(g) + H_2O(l) \rightarrow 2HNO_3(aq) + NO(g)$$

A second problem linked to increased levels of oxides of nitrogen is the formation of **photochemical smog**. Smog results when several air pollutants react with sunlight to form the characteristic brown haze seen over many large cities.

Photochemical smog is harmful to human health. It has been linked to respiratory disease and increased numbers of asthma attacks.

Although oxides of nitrogen can form naturally, most come from human activity. These include vehicle emissions, power production and other industrial processes. The extent to which human activity produces NO_x was shown by the dramatic reduction in airborne nitrogen oxide pollution during the lockdowns enforced as part of the response to the COVID-19 worldwide pandemic.

In a car engine, nitrogen oxides are produced due to the very high temperatures. These high temperatures allow nitrogen from the air, generally a very unreactive gas, to react with oxygen, also from the air. One way to reduce levels of NO_x emitted by vehicles is to use a **catalytic converter** connected as part of the exhaust system. The toxic gases produced by the engine are converted into less harmful gases before they are emitted into the atmosphere.

A catalytic converter uses a rare transition metal catalyst (e.g. platinum, palladium or rhodium), which is coated as a thin layer onto a honeycomb support. Within a catalytic converter, carbon monoxide will react with nitrogen oxide to release carbon dioxide and nitrogen:

carbon monoxide	+	nitrogen oxide	→	carbon dioxide	+	nitrogen
$2CO(g)$	+	$2NO(g)$	→	$2CO_2(g)$	+	$N_2(g)$

Catalytic converters can also catalyse other reactions to further reduce the emissions of pollutant gases.

Carbon monoxide

Incomplete combustion occurs when a hydrocarbon fuel is burnt in a limited supply of oxygen. When this happens, one possible product is the pollutant carbon monoxide (CO). The incomplete combustion of octane (an important constituent of petrol) is shown by:

octane	+	oxygen	→	carbon monoxide	+	water
$2C_8H_{18}$	+	$17O_2$	→	$16CO$	+	$18H_2O$

This should be compared to **complete combustion** of hydrocarbon fuels that occurs in a plentiful supply of oxygen and releases only carbon dioxide and water.

Carbon monoxide is toxic to humans because it binds very strongly with haemoglobin in red blood cells, preventing them from carrying oxygen around the body.

Carbon monoxide can be produced when there is a shortage of oxygen getting into an engine. It can also be made when the air inlets get blocked in a gas central heating system as this prevents oxygen from entering the system.

To reduce emissions of carbon monoxide from vehicles a catalytic converter is fitted. This converts carbon monoxide into carbon dioxide, as shown in the previous equation.

Particulates

Like carbon monoxide, carbon particulates ('soot' particles) are formed as a result of incomplete combustion of fuel. The incomplete combustion of octane to form particulates is shown by:

octane	+	oxygen	→	particulate (soot)	+	water
$2C_8H_{18}$	+	$9O_2$	→	$16C$	+	$18H_2O$

Particulates are linked to increased respiratory disease and there is also evidence that they can cause cancer.

KEY WORDS

photochemical smog: a form of local atmospheric pollution found in large cities in which several gases react with each other to produce harmful products.

catalytic converter: a device for converting polluting exhaust gases from cars into less dangerous emissions.

incomplete combustion: a type of combustion reaction in which a fuel is burnt in a limited supply of oxygen; the incomplete combustion of hydrocarbon fuels produces carbon, carbon monoxide and water.

complete combustion: a type of combustion reaction in which a fuel is burnt in a plentiful supply of oxygen; the complete combustion of hydrocarbon fuels produces only carbon dioxide and water.

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An important source of particulates is from diesel vehicles where they are produced because of a shortage of oxygen getting into an engine. To reduce particulate emissions, diesel vehicles are fitted with particulate traps (fine mesh filters) that remove the particles from the exhaust gas.

Questions

C10.01 What are the percentages of nitrogen, argon and oxygen in clean dry air?

C10.02 Describe some of the problems caused by acid rain.

C10.03 Fuels undergo either complete or incomplete combustion in oxygen.

a State the word equation for the incomplete combustion of methane to produce carbon monoxide and water.

b Balance this symbol equation:

$$\_\_\_C_6H_{14} + \_\_\_O_2 \rightarrow \_\_\_\_CO + \_\_\_\_H_2O$$

C10.04 Explain how oxides of nitrogen are formed and give some of the problems they are linked to.

C10.05 Give a balanced symbol equation to show how a catalytic converter can remove carbon monoxide (CO) and nitrogen oxide (NO) from the exhaust gases to produce only nitrogen and carbon dioxide.

Carbon dioxide, methane and climate change

Greenhouse gases

Carbon dioxide, although produced naturally by respiration, is considered a particularly important pollutant. It is one of the **greenhouse gases** and increased amounts in the atmosphere have resulted in global warming. Global warming causes an increase in average temperatures and, because of this, is leading to climate change. There are several greenhouse gases including water vapour, carbon dioxide, methane, nitrous oxide, sulfur hexafluoride and chlorofluorocarbons (CFCs). In this topic we will only look at two main greenhouse gases: carbon dioxide and methane.

Release of carbon dioxide into the atmosphere

Carbon dioxide (CO_2) is produced during the complete combustion of fossil fuels. Fossil fuels are used to produce electricity and are the basis of many forms of transport. For example, methane (natural gas) produces carbon dioxide when burnt in a plentiful supply of oxygen:

methane	+	oxygen	→	carbon dioxide	+	water
CH_4	+	$2O_2$	→	CO_2	+	$2H_2O$

Release of methane into the atmosphere

Like carbon dioxide, methane (CH_4) is a greenhouse gas. Levels of methane in the atmosphere have increased over recent years. Some of the reasons for rising levels of methane in the atmosphere are linked to increased cattle farming and more waste being generated by larger populations. Cattle emit large amounts of methane as part of their digestive system. A single cow can produce over 1000 times the mass of methane produced by a human. The decomposition of food waste under anaerobic conditions by bacteria at landfill sites also releases large amounts of methane into the atmosphere.

Global warming

Carbon dioxide and methane occur naturally in the atmosphere and play an important role in maintaining a constant temperature on Earth. This relatively constant temperature is due to a natural phenomenon that scientists call the **greenhouse effect**. By trapping thermal energy reflected from the Earth's surface, the greenhouse gases maintain an average surface temperature of around 15 °C. Without the greenhouse effect, the average temperature would be much lower, possibly only −18 °C. At this temperature, life of the type we know would not exist. Over the last 200 million years, levels of greenhouse gases have remained relatively constant but, because of human activity, this is now starting to change. Increased use of fossil fuels and changes in farming have caused levels of carbon dioxide and methane to rise. This, in turn, has resulted in an increase in the average surface temperature of the Earth. The increase is known as global warming and it has resulted in changing weather patterns (climate change).

Scientists have linked global warming to increased levels of greenhouse gases because of the strong correlations between the concentration of the gases in the atmosphere and the average recorded temperatures.

KEY WORDS

greenhouse gas: a gas that absorbs heat reflected from the surface of the Earth, stopping it escaping the atmosphere.

greenhouse effect: the natural phenomenon in which thermal energy (heat) from the Sun is 'trapped' at the Earth's surface by certain gases in the atmosphere (greenhouse gases).

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Greenhouse effect

The greenhouse gases allow high-energy, short wavelength radiation from the Sun to pass through the atmosphere and reach the Earth's surface. Some of this thermal energy is absorbed and heats the oceans and land, and some is radiated (reflected) back into the atmosphere. The heat radiated by the Earth has a lower energy and a longer wavelength. The actual wavelength of this reflected radiation falls within the infrared part of the electromagnetic spectrum. The greenhouse gases, such as carbon dioxide and methane, can absorb this infrared radiation and then re-radiate (re-emit) it in all directions. As it is re-emitted in all directions, some comes back towards the Earth's surface. This reduces the heat loss to space and increases the temperature of the lower atmosphere. This phenomenon is called the greenhouse effect because the absorption and reflection of heat that warms the atmosphere works in a similar way to a greenhouse (Figure C10.05).

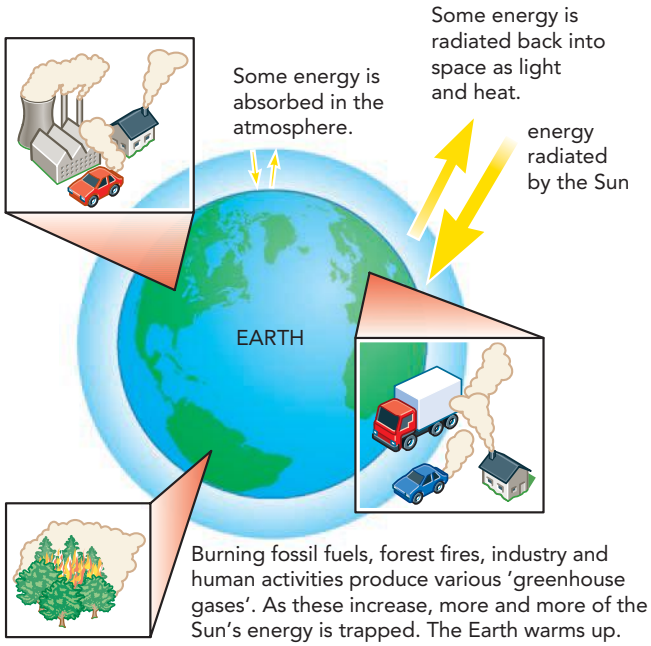

Figure C10.05: The greenhouse effect.

Climate change

Global warming has brought about a range of consequences for the Earth's climate. The impacts of global warming differ from country to country and general changes in weather patterns are known collectively as climate change.

An important impact of climate change is that the increase in average temperature has caused quicker rates of melting of the Earth's polar ice caps and glaciers. This has led to rising sea levels and so there has been increased flooding in some low-lying countries and faster rates of coastal erosion. The melting of ice caps is also causing changes to the life cycles and migratory patterns of animals and birds. Polar bears, who rely on sea ice as they travel between different hunting grounds, have been particularly badly affected.

An increase in temperature can also lead to more severe droughts. With higher temperatures, the soil dries out more quickly, and this is then compounded by changes in rainfall. Very dry soil and low rainfall increase the chances of crop failure. In the longer term, arable land can become so arid it turns to desert. In regions such as California and parts of Australia, drying out of grasslands as a result of climate change has increased the frequency and severity of wildfires.

The problems linked to climate change are not limited to increased temperatures. For many countries, climate change means more frequent, more extreme weather patterns. For some this has included more severe storms and associated flooding and landslides.

While the effects of climate change can be disruptive to human ways of living, they can be catastrophic for animals and plants. Many living organisms are extremely sensitive to even slight changes in average temperature. For example, changes in temperature can lead to differences in the seasons when plants bud and produce fruit, which then has consequences for the wildlife whose life cycles depend on these plants. Changes in sea temperature can lead to bleaching of coral reefs and the associated loss of marine life.

Reducing the amount of CO_2 released into the atmosphere

There are many steps that can be taken to reduce the release of greenhouse gases at the individual, national and global levels. In recent years, governments from around the world have tried to take steps together to reduce their greenhouse gas emissions. There have been important climate change conferences where agreements have been made, including the Kyoto Protocol of 2005 and the Paris Agreement of 2016. Increased public awareness of the impact of climate change and a stronger presence of environmental groups has placed pressure on governments to react.

An important step towards decreased greenhouse gas emissions of carbon dioxide is to reduce our reliance on fossil fuels for transportation and electricity generation. This can be done by turning to **renewable** sources of energy such as wind and solar. Many countries have started to remove coal power stations and replace them with renewable energy sources.

KEY WORD

renewable: sources of energy and other resources that cannot run out provided they are managed sustainably, or that can be made at a rate faster than our current rate of use.

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Methods of transport are starting to change, and several countries have committed themselves to the phasing out of diesel engines. There is significant interest in moving away from petrol cars to electric cars, although there are still issues about how the electricity used to power these vehicles is created. Some manufacturers are also looking at developing fuel cell vehicles. Hydrogen fuel cells are of particular interest as the only chemical product is water (Chapter C6). An alternative method being used by many countries is to plant additional trees (afforestation) which will capture the CO_2 through photosynthesis.

Reducing the amount of methane released into the atmosphere

Methane is released by both rotting vegetation and livestock. Innovative approaches have been considered to reduce methane emissions from livestock, including changes in their diet and even trying to capture the gases they produce.

In the short term, a more realistic option for reducing methane emissions from cattle is to better educate people about the harmful effects of an excessively meat-rich diet. There is evidence that encouraging greater dependence on plant-based food is being successful, with increasing numbers of vegetarians and vegans around the world.

Questions

C10.06 Name *two* greenhouse gases and give a source for each.

C10.07 Why are levels of carbon dioxide in the atmosphere increasing?

C10.08 What are some of the problems linked to climate change and the melting of the ice caps? List some of the strategies that could be used to reduce these environmental issues.

C10.09 The greenhouse gases allow short wavelength, high-energy radiation from the Sun to pass through the atmosphere. What do they do to the longer wavelength radiation reflected into space from the Earth's surface?

REFLECTION

How easy do you find it to apply your scientific understanding to issues such as global warming and climate change? Could you explain these environmental issues to someone else? Are there any other factors you would need to consider?

How can the scientific knowledge you have learnt benefit people and the environment?

C10.02 Water

Water is vital to life and plays an important role in many industrial processes. In this topic, we will consider how to test for the presence of water, and look at the differences between distilled water and drinking water ('potable' water).

Tests for the presence and purity of water

There are many colourless liquids, including water, ethanol and cyclohexane. So, how do we know whether water is present? Either of two simple chemical tests can be used to show the presence of water. Blue cobalt chloride paper turns pink in the presence of water (Figure C10.06). Anhydrous cobalt(II) chloride is converted to the hydrated salt.

$$\underset{\text{blue}}{CoCl_2} + 6H_20 \rightarrow \underset{\text{pink}}{CoCl_2 \cdot 6H_20}$$

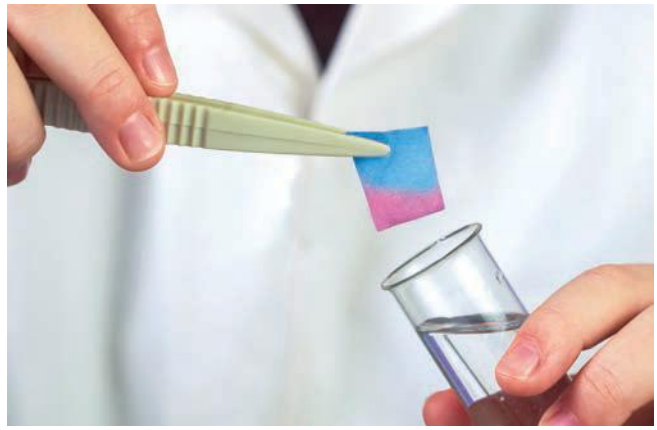

Figure C10.06: Test for the presence of water: blue cobalt chloride paper turns pink. Note the use of tweezers when handling the test paper.

Alternatively, solid white anhydrous copper(II) sulfate forms blue hydrated copper(II) sulfate ($CuSO_4 \cdot 5H_2O$) if water is added to it.

$$\underset{\text{white}}{CuSO_4} + 5H_2O \rightarrow \underset{\text{blue}}{CuSO_4 \cdot 5H_2O}$$

The purity of any substance, including water, can be tested by recording its melting and boiling points. This is because pure water has a fixed melting point of 0 °C and boiling point of 100 °C. The temperature at which water boils or melts will be affected by any impurities present.

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Distilled water

Tap water is a mixture of natural minerals (dissolved salts) and substances added due to human activity. Experiments that require water as a solvent should use distilled water rather than tap water. This is because substances dissolved in the tap water may interfere with experiments, giving unwanted side reactions. They would also interfere with the results of standard analysis, e.g. for metal ions. Distillation (Chapter C12) removes the impurities and uses the key idea that different substances have different boiling points due to differences in mass and the interactions between their molecules.

Purification of domestic water

Tap water, the domestic water supplied to our houses, undergoes several purification steps from the point it is collected to the point it is delivered. In many countries, domestic water is taken from lakes and reservoirs.

The first step in purification is to remove large insoluble objects such as rocks, plastic bags and branches, in a process known as screening. The water is then taken to a sedimentation tank. In the sedimentation tank, the soil and sand will drop to the bottom of the tank (as sediment).

The next step in the process is to filter the water to remove smaller insoluble particles. The water is often passed through a very fine sand to filter out these particles.

Water may contain dissolved organic compounds that can cause the water to have an unwanted odour or taste. The organic compounds, often present in exceptionally low amounts, can be removed by using an activated carbon filter.

Before water is distributed to homes, the final step is disinfection. Disinfection is needed to kill harmful waterborne microbes such as bacteria that can cause disease. Different countries use different methods to disinfect water but one of the most common and effective methods is to add small amounts of chlorine to the water. Typically, chlorine is added at a concentration of 2–3 mg/dm^3.

A summary of the main stages involved in water treatment is shown in Figure C10.07.

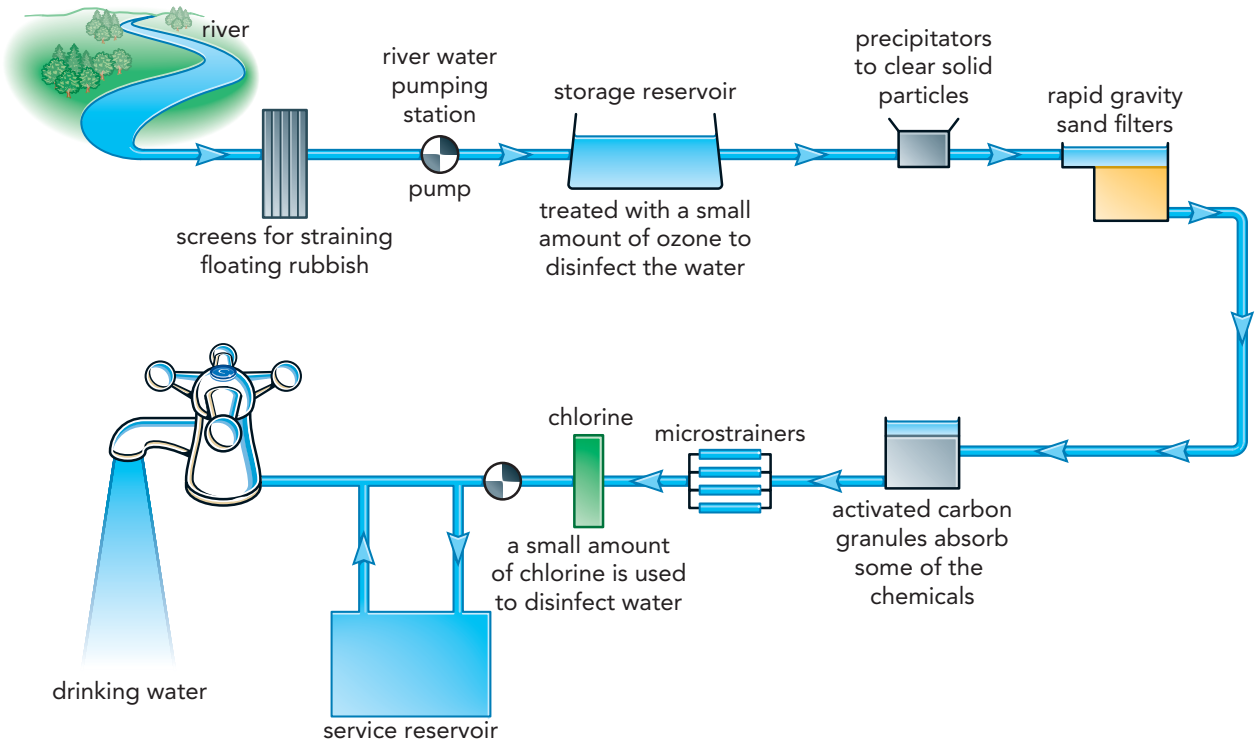

Figure C10.07: Purifying water for the domestic water supply.

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Questions

C10.10 State a simple test, giving its result, for detecting the presence of water.

C10.11 How could you prove that a sample of water was pure?

C10.12 Water from a lake contained microplastics, traces of dissolved organic compounds and microbes linked to diarrhoea. How would these three contaminants be removed to enable the water to be sold as domestic water?

ACTIVITY C10.01

A letter of concern

Research the pollutants which are an issue in your local environment/country or globally. Write a letter of concern to your local government explaining your concerns and setting out steps that you feel they should take, and why.

- In the first paragraph, you should state the importance of reducing pollutants. You need to give examples of the problems that pollutants cause.
- In the second paragraph, you need to suggest steps to reduce the levels of pollutants.
- You should finish your letter with a reminder of the importance of clean water and air and the need for local areas/countries to work together.

Self assessment

List *three* criteria for a good explanation of an environmental concern. How well do you think your explanations about the effects of pollutants have met these criteria? Can you rewrite one of your explanations adding further improvements?

PROJECT C10.01 THE GREAT ENERGY DEBATE

Your government needs to plan its energy resources for future use (Figure C10.08). In a group of three, organise a debate, putting forward different ideas for the plan.

- Person 1: You work for the oil industry. In your presentation you must give reasons why it is necessary to continue burning fossil fuels. You should think about the ways in which fossil fuels are used (e.g. transport and heating) and the problems in swapping to alternatives. You might also want to state ways in which you have made improvements in how fossil fuels are being used.
- Person 2: You represent suppliers of renewable energy. In your presentation you need to explain the benefits of moving to renewable fuels. Think about the emissions benefits but also any logistical concerns.
- Person 3 (the chair or judge): You will need to listen to the presentations from each person and then ask them additional questions.

At the end of the debate, the group should produce a brief summary of the arguments and reach a consensus in order to produce an outline of a recommended plan for your government to use.

Figure C10.08: Green energy versus polluting energy.

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SUMMARY

The atmosphere is made up of a mixture of gases and includes a variable amount of water vapour.
Clean dry air (air without water vapour) is a mixture of nitrogen (78%), oxygen (21%), noble gases and carbon dioxide.
The main air pollutants include carbon dioxide (CO_2), methane (CH_4), oxides of nitrogen (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO) and carbon particulates.
Oxides of nitrogen, NO_x, are formed when nitrogen and oxygen from the air react at high temperature. They can cause respiratory problems, acid rain and photochemical smog.
NO_x can be removed by the use of a catalytic converter.
In a catalytic converter, CO and NO_x react to produce nitrogen and carbon dioxide.
SO_2 is formed when sulfur in fossil fuels reacts with oxygen during combustion. SO_2 reacts with water vapour to form acid rain.
Levels of SO_2 can be reduced by using ultra low sulfur fuels (desulfurisation of fossil fuels).
Levels of SO_2 can be reduced by neutralisation of flue gases.
CO and carbon particulates are products of incomplete combustion of fossil fuels and can cause health problems. CO can be removed from exhaust gases using a catalytic converter and carbon particulates are removed by using a particulate trap.
CO_2 is a greenhouse gas produced by the combustion of fossil fuels. CH_4 is a greenhouse gas released by cattle and from rotting vegetation at landfill sites.
Greenhouse gases allow short wavelength energy from the Sun to reach the Earth's surface but trap and re-emit the longer wavelength radiation reflected from the Earth.
Increased levels of greenhouse gases in the atmosphere have caused an increase in average temperatures (global warming), which has a range of important environmental effects.
Strategies to reduce the effects of these environmental issues include using renewable sources of energy, decreasing the use of fossil fuels, planting more trees and a reduction in livestock farming.
The presence of water can be determined by using anhydrous copper(II) sulfate, which turns from white to blue with water, or anhydrous cobalt(II) chloride, which turns from blue to pink with water.
The purity of water can be assessed by its melting point (0 °C) and boiling point (100 °C).
Distilled water is used in practical experiments because it contains fewer impurities than tap water.
Domestic water supplies go through several purification steps, including screening, sedimentation and filtration (to remove solids), carbon filtration (to remove odours and taste) and chlorination (to kill harmful microbes).

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PRACTICE QUESTIONS

1 The domestic water supply is treated in various ways to make it safe for use. **Identify** which of the following treatments is designed to kill any bacteria present in the water.

A sedimentation
B filtration through gravel beds
C treatment with chlorine
D passage through a carbon filter [1]

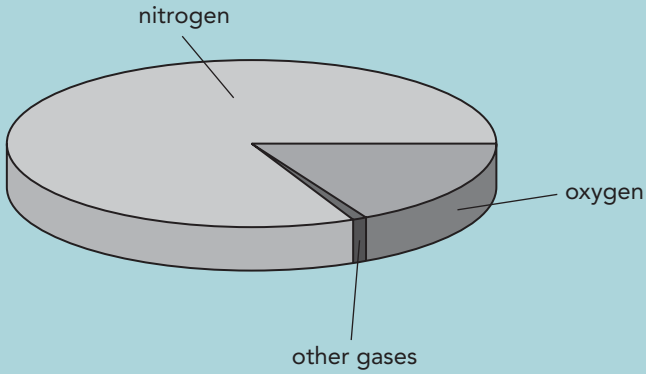
2 The reaction shown occurs in catalytic converters.

$$2NO_2(g) + 4CO(g) \rightarrow 4CO_2(g) + N_2(g)$$

Identify which statement about this reaction is true.

A Carbon monoxide is an oxidising agent and is oxidised to carbon dioxide.
B Carbon monoxide is a reducing agent and is oxidised.
C Nitrogen dioxide is an oxidising agent and oxidises nitrogen.
D Nitrogen dioxide is a reducing agent and reduces carbon monoxide. [1]

3 The pie chart shows the composition of clean dry air.



a **State** the percentage of nitrogen in clean dry air. [1]

b Apart from nitrogen and oxygen, state the names of two other gases present in clean dry air. [2]

c The following questions relate to these four gases, which are all found as air pollutants.

A carbon monoxide **B** methane
C oxides of nitrogen **D** sulfur dioxide

i Identify the gas given off from the farming of cattle. [1]
ii Identify the gas produced when fuels burn incompletely. [1]
iii State which gases cause acid rain. [2]
iv State which gases are a harmful component of photochemical smog. [1]

[Total: 8]

COMMAND WORD

identify: name/select/recognise.

COMMAND WORD

state: express in clear terms.

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CONTINUED

4 The burning of fossil fuels is the main source of air pollution. Fuels are burnt in vehicles and in power stations to make energy.

a **Describe** how the burning of fossil fuels causes pollution of water in rivers and lakes. **[2]**

b Carbon monoxide is produced in motor car engines.

i State why carbon monoxide is produced instead of carbon dioxide. **[1]**

ii **Suggest** why carbon monoxide is harmful. **[1]**

c When coal is burnt in power stations, sulfur dioxide is one of the pollutants formed. Describe how power stations can prevent sulfur dioxide from entering the atmosphere. **[2]**

d Oxides of nitrogen are produced in motor car engines. State where the oxygen and nitrogen come from. **[1]**

[Total: 7]

5 **a** Carbon dioxide in the atmosphere can cause global warming.

State how CO_2 is produced and why levels of CO_2 need to be reduced. **[2]**

b Identify another gas that also causes global warming and give one natural source of this gas. **[2]**

c **Explain** how the gases you have named caused global warming. **[3]**

[Total: 7]

COMMAND WORDS

describe: state the points of a topic / give characteristics and main features.

suggest: apply knowledge and understanding to situations where there are a range of valid responses in order to make proposals / put forward considerations.

COMMAND WORD

explain: set out purposes or reasons/make the relationships between things clear/say why and/or how and support with relevant evidence.

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SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
state the composition of clean dry air	C10.01			
give the sources of the main pollutants: NO_x, sulfur dioxide, carbon monoxide, particulates, carbon dioxide and methane	C10.01			
state the problems caused by NO_x, sulfur dioxide, carbon monoxide and particulates	C10.01			
describe ways of reducing sulfur dioxide and NO_x	C10.01			
state that carbon dioxide and methane are greenhouse gases, which at higher concentrations lead to global warming and the associated climate change	C10.01			
describe how the greenhouse gases cause global warming	C10.01			
give ways in which climate change can be reduced	C10.01			
describe tests for the presence of water	C10.02			
describe tests for the purity of water	C10.02			
explain why distilled water is used in practical chemistry	C10.02			
describe the main stages in the purification of the domestic water supply.	C10.02			

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C11

Organic chemistry

All learners study some content in this chapter

IN THIS CHAPTER YOU WILL:

- understand that compounds containing at least one carbon–carbon double or triple bond are unsaturated molecules and that saturated compounds contain only single bonds
- learn that a homologous series of organic compounds has the same general formula and similar chemical properties
- describe the general characteristics of a homologous series
- learn to name and draw the displayed formulae of methane, ethane, ethene and ethanol
- understand that suffixes tell us the family an organic molecule belongs to
- understand how to draw structural and displayed formulae of unbranched members of different homologous series
- state that alkanes are saturated compounds as all the carbon–carbon bonds are single covalent bonds
- describe the alkanes as a series of generally unreactive compounds that burn readily

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CONTINUED

- state that alkenes are unsaturated compounds as they contain carbon–carbon double bonds
- describe how to test for saturated and unsaturated hydrocarbons
- understand that alkenes can be obtained by catalytic cracking
- describe how alkenes take part in addition reactions
- describe the complete combustion of ethanol and that alcohols are used as fuels and solvents
- learn that the major fossil fuels are coal, natural gas and petroleum
- know that hydrocarbons are compounds containing carbon and hydrogen only
- describe how fractional distillation can be used to separate petroleum into a range of fractions
- describe how the properties of the fractions vary
- define polymers as long-chain molecules built up from smaller molecules (monomers) using polyethene as an example
- identify the structure of an addition polymer or its repeat unit
- understand that polymers can also be formed by condensation reactions
- identify the repeat unit in a condensation polymer
- describe the differences between addition and condensation polymerisation.

BEFORE YOU START

What do you understand by the word 'organic'? The word has been linked to ideas related to the natural world. Organic molecules were once believed to have distinctive chemical properties, making them unique to living organisms. It was believed that there was a separate chemistry that took place in living things.

In groups, discuss your understanding of the word and make a list of any substances that you would think of as being organic. What element do they all contain? What molecules do we search for on other planets and in the dust of comets that would be evidence for life other than on Earth? Then come together as a class to share your ideas.

SCIENCE IN CONTEXT C11.01

Building a space elevator

Carbon is a non-metal in Group IV of the Periodic Table. The uniqueness of carbon lies in the different ways in which it can form bonds. This shows even in the element itself. Carbon exists in several different forms (Chapter C3). The fullerenes, carbon nanotubes and graphene, have been discovered relatively recently and the exploitation of these types of carbon is one of the major features of the exciting new area of nanotechnology.

One important property of carbon nanotubes and graphene is their amazing tensile strength. These structures are far stronger than steel or titanium. Carbon nanotubes and graphene also show very high electrical conductivity. The prospect of using these new materials for the elevator cable has given new belief in the idea of constructing a space elevator (Figure C11.01).

The idea of a space elevator to carry humans into orbit is not new – the Russian scientist Konstantin Tsiolkovsky envisaged something like it at the end of the 19th century. However, today technology is being developed to move the idea towards reality. The elevator would comprise a huge (50 km) base tower on Earth, with a cable connected to it that stretches into space to a point beyond geostationary orbit, at an altitude of more than 35 000 km. Tracks and platforms along the tower and cable would allow vehicles to move to different levels, including into orbit without the need to use large rockets.

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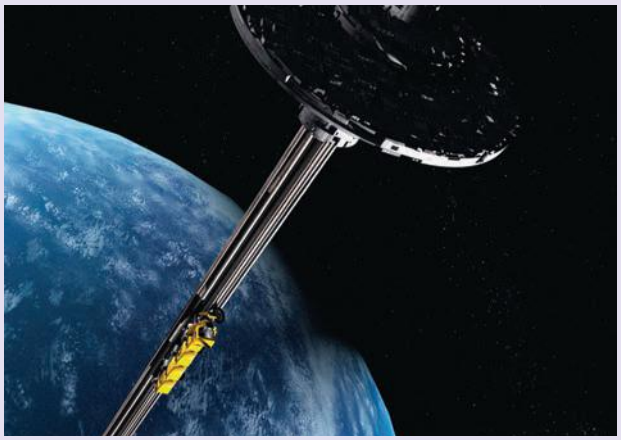

Figure C11.01: Computer artwork of a future space elevator viewed looking down the length of the elevator cable towards the Earth.

Preliminary experiments on aspects of the design of a space elevator have been conducted from the International Space Station. Companies in Japan and China have expressed an interest in developing such an elevator and an International Space Elevator Consortium has been set up. One development that must be explored is that of generating nanotube or graphene structures for the cable that are much longer than those currently available (Figure C11.01). However, the possibilities created by these new materials are quite staggering.

Discussion questions

1 What do you understand of the purposes and advantages of developing a space elevator?

2 Research and discuss the structural similarities between graphite, graphene and the fullerenes to explain why they are able to conduct electricity even though they are non-metallic.

C11.01 Formulae and terminology

Carbon's unique properties

Carbon is unique in the variety of molecules it can form. The chemistry of carbon-containing compounds is known as **organic chemistry**. There are three special features of covalent bonding involving carbon (Figure C11.02):

- Carbon atoms can join to each other to form long chains (Figure C11.02a); atoms of other elements can then attach to the chain (Figure C11.02b).
- The carbon atoms in a chain can be linked by single, double or triple covalent bonds (Figure C11.02c).
- Carbon atoms can also arrange themselves in rings (Figure C11.02d).

Only carbon can achieve all these different bonding arrangements to this extent. Indeed, there are more compounds of carbon than of all the other elements put together.

Figure C11.02 gives some idea of how these bonding arrangements can produce different types of molecule.

KEY WORDS

organic chemistry: studies on the structure, properties and reactions of organic compounds that contain carbon in covalent bonding.

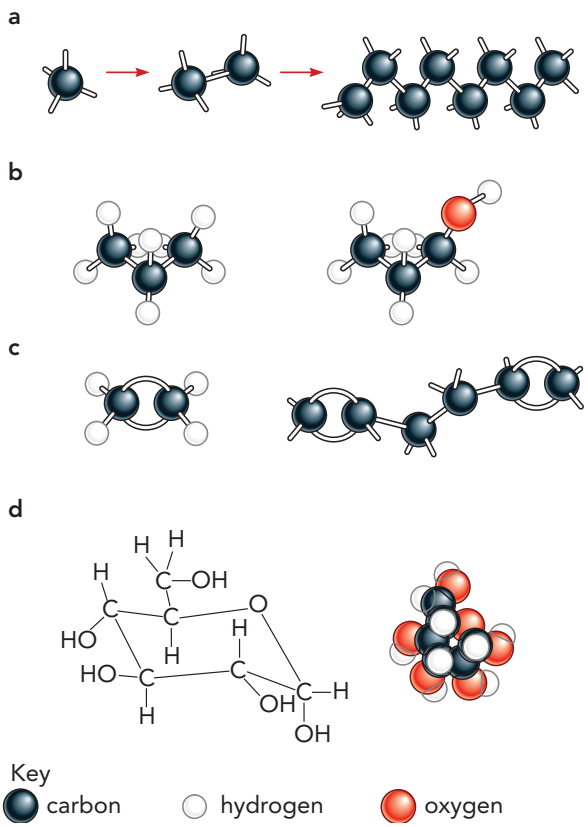

Figure C11.02: Carbon is very versatile and able to form chain and ring structures.

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Hydrocarbons

One of the simplest types of organic compound is the **hydrocarbon**. Hydrocarbons are compounds that contain carbon and hydrogen *only*.

The hydrocarbons studied at this level can be subdivided into two 'families' of molecules. Some hydrocarbons are saturated. These molecules contain only single covalent bonds between carbon atoms. Since carbon has a valency of 4, the bonds not used in making the chain are linked to hydrogen atoms. No further atoms can be added to molecules of these compounds, which is why we say they are saturated. This family of **saturated hydrocarbons** is known as the **alkanes**.

By contrast, **unsaturated hydrocarbons** contain double or triple bonds. The family of hydrocarbons that contain double bonds are called **alkenes**.

KEY WORDS

hydrocarbon: organic compound that contains carbon and hydrogen only; the alkanes and alkenes are two series of hydrocarbons.

saturated hydrocarbon: hydrocarbon molecule in which all the carbon–carbon bonds are single covalent bonds.

alkanes: a series of hydrocarbons with the general formula C_nH_{2n+2}; they are saturated compounds as they have only single bonds between carbon atoms in their structure.

unsaturated hydrocarbon: hydrocarbon whose molecule contains at least one carbon–carbon double or triple bond.

alkenes: a series of hydrocarbons with the general formula C_nH_{2n}; they are unsaturated compounds as they contain carbon–carbon double bonds.

Homologous series

As we can see from the examples above, organic molecules are organised in families, such as alkenes and alkanes. All the molecules within one of these families will have similar structures and similar chemical properties. These similarities come about because all the molecules within a **homologous series** contain the same **functional group** (Table C11.01). The functional group is the group of atoms responsible for the characteristic reactivity of the homologous series.

When we consider a homologous series we will find that the members all have the same **general formula**. For example, the formulae for the first six alkanes are shown in Table C11.02. Here we can see that all the molecular formulae fit the pattern of C_nH_{2n+2}.

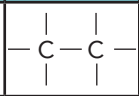
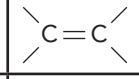
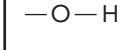
Homologous series	Name ending	Functional group	General formula	First member of series
alkanes	-ane		C_nH_{2n+2}	methane (n = 1)
alkenes	-ene		C_nH_{2n}	ethene (n = 2)
alcohols	-ol		$C_nH_{2n+1}OH$	methanol (n = 1)

Table C11.01: Different homologous series.

Different homologous series will have different general formulae, but the general formula will be consistent within each series. These general formulae allow us to work out the formula of a compound within a series, e.g. an alkene with four carbons will have $n = 4$, therefore the formula will be C_4H_8.

Alkane	Number of carbon atoms	Prefix to name	Molecular formula (C_nH_{2n+2})	Boiling point / °C
methane	1	meth-	CH_4	–162
ethane	2	eth-	C_2H_6	–89
propane	3	prop-	C_3H_8	–42
butane	4	but-	C_4H_{10}	0
pentane	5	pent-	C_5H_{12}	36
hexane	6	hex-	C_6H_{14}	69

Table C11.02: Names and molecular formulae of the alkanes.

KEY WORDS

homologous series: a family of similar compounds with similar chemical properties due to the presence of the same functional group.

functional group: the atom or group of atoms responsible for the characteristic reactions of a compound.

general formula: an algebraic formula that describes all members of a homologous series, e.g. for alkanes C_nH_{2n+2}.

From Table C11.02 and Figure C11.03 we can also see that there is a trend in boiling point within the alkanes. As the length of the hydrocarbon chain increases, the strength of the weak forces between the molecules (intermolecular forces) is increased.

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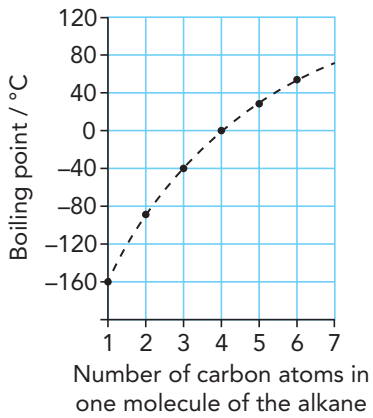

Figure C11.03: Plot of the boiling points of the first six straight-chain alkanes (methane to hexane).

This shows itself in the increasing boiling points of the members of the series. Under normal conditions, the first four members of the straight-chain alkanes are gases, and those between C_5H_{12} and $C_{16}H_{34}$ (which are called C_5 to C_{16} alkanes) are liquids. The compounds in the alkane family with 17 or more carbon atoms are waxy solids.

Similar graphs can be plotted for the melting points and densities of the alkanes. The values of these physical properties show a progressive increase with increasing chain length. The same trends in physical properties are observed in other homologous series such as the alkenes or alcohols. This adds a further general feature to the characteristics of a homologous series.

A homologous series is, therefore, a series of organic molecules having:

- the same functional group
- the same general formula
- members that differ from one to the next by a $–CH_2–$ unit
- a consistent trend in physical properties with increasing molecular size
- similar chemical properties.

C11.02 Naming organic compounds

Formulae and information

Every organic compound can be represented by several different types of formulae. These formulae are designed to give us information about the composition and nature of the compound. The first is the *molecular formula*. This represents the number of atoms present in the molecule; thus, for methane it is CH_4, for ethane it is C_2H_6, and so on.

The molecular formula does not indicate the structure of the molecule, simply the atoms present. It is the **displayed formula** for the compound that gives us the arrangement of the atoms. A displayed formula shows the structure and all the bonding in the molecule. Examples of displayed formulae can be seen in Figure C11.04.

Drawing the displayed formula each time we refer to a compound can be unnecessary. A **structural formula** is designed to show information on structure without showing all the bonds. The two straight-chain structural isomers of butene can be written as $CH_3CH_2CH{=}CH_2$ (but-1-ene) and $CH_3CH{=}CHCH_3$ (but-2-ene), for instance. Here, the number added to the formula indicates the position of the double bond. To work this out, the carbon atoms are numbered from the end of the chain. In but-1-ene the double bond is between carbon atoms 1 and 2, whereas in but-2-ene it is between carbon atoms 2 and 3.

Further examples of structural and molecular formulae are shown in Table C11.03.

Homologous series	Compound	Molecular formula	Structural formula
alkanes	ethane	C_2H_6	CH_3CH_3
	propane	C_3H_8	$CH_3CH_2CH_3$
alkenes	ethene	C_2H_4	$CH_2{=}CH_2$
	propene	C_3H_6	$CH_3CH{=}CH_2$
alcohols	ethanol	C_2H_5OH	CH_3CH_2OH
	propanol	C_3H_7OH	$CH_3CH_2CH_2OH$
carboxylic acids	ethanoic acid	CH_3COOH	CH_3COOH
	propanoic acid	C_2H_5COOH	CH_3CH_2COOH

Table C11.03: Structural formulae of representative molecules from different homologous series.

KEY WORDS

displayed formula: a representation of the structure of a compound that shows all the atoms and bonds in the molecule.

structural formula: the structural formula of an organic molecule shows how all the groups of atoms are arranged in the structure; ethanol, CH_3CH_2OH, for example.

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C11.03 Alkanes

The alkanes are a homologous series of saturated hydrocarbons. The simplest alkane contains one carbon atom and is called methane. The series of alkane compounds is built up by simply adding an extra $–CH_2–$ group to the chain.

The formulae of these molecules all fit the general formula C_nH_{2n+2} (where n is the number of carbon atoms present). Therefore, if you know the number of carbon atoms in an alkane molecule, then you can always work out the molecular formula.

Note that the names of this series of hydrocarbons all end in *-ane*. The first part of the name (the prefix) tells you the number of carbon atoms in the chain. These prefixes are used consistently in naming organic compounds.

The alkanes are quite unreactive compounds. Alkanes are saturated molecules, so they cannot take part in **addition reactions**. They are unaffected by acids or alkalis. However, they do undergo combustion.

KEY WORDS

addition reaction: a reaction in which a simple molecule adds across the carbon–carbon double bond of an alkene.

Combustion of alkanes

Alkanes burn readily (Figure C11.05). When they burn in a good supply of air, the products are carbon dioxide and water vapour:

methane + oxygen → carbon dioxide + water

$$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g)$$

ethane + oxygen → carbon dioxide + water

$$2C_2H_6(g) + 7O_2(g) \rightarrow 4CO_2(g) + 6H_2O(g)$$

butane + oxygen → carbon dioxide + water

$$2C_4H_{10}(g) + 13O_2(g) \rightarrow 8CO_2(g) + 10H_2O(g)$$

The same products are obtained whichever alkane is burnt, so long as there is a sufficient oxygen supply. Note that the key to balancing the symbol equations for these reactions is to balance the oxygen correctly.

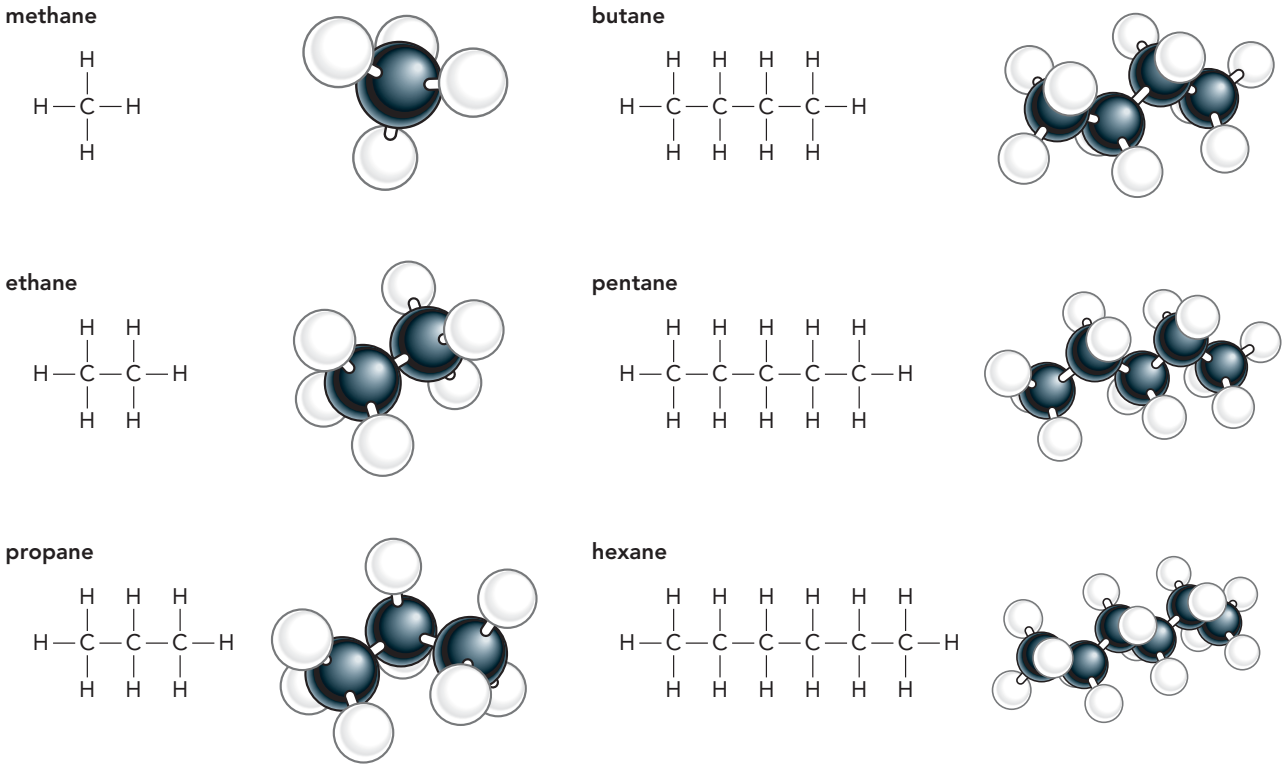

Figure C11.04: Displayed formulae and structures of the first six alkanes.

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Figure C11.05: Excess natural gas (mainly methane) is sometimes flared off at oilfields.

C11.04 Alkenes

The ability of carbon atoms to form double bonds with each other gives rise to the alkenes. The alkenes are another family of hydrocarbons. Alkenes have the general formula C_nH_{2n}. Note that there are two fewer hydrogen atoms compared with a similar alkane because of the presence of the carbon–carbon double bond. The presence of a carbon–carbon double bond means that alkenes are unsaturated. The simplest alkene *must* contain two carbon atoms (which are needed for one carbon–carbon double bond to be formed). It is called ethene. Figure C11.06 shows a dot-and-cross diagram of the bonding in ethene and also the structures of the first three alkenes. You will note that the names of all the alkenes end with *-ene*.

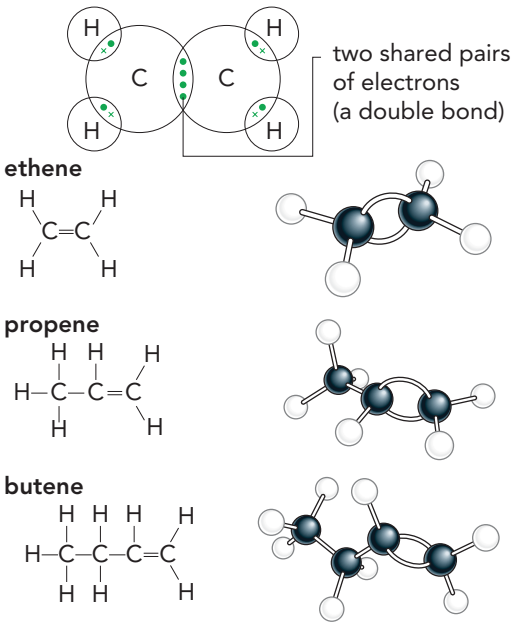

Figure C11.06: Bonding in ethene and structures of the first three alkenes.

Table C11.04 shows the names and molecular formulae of the first five alkenes. Note that the same prefixes used for the alkanes are also used to indicate the number of carbon atoms in the molecules of the alkenes.

Alkene	Number of carbon atoms	Prefix to name	Molecular formula (C_nH_{2n})
ethene	2	eth-	C_2H_4
propene	3	prop-	C_3H_6
butene	4	but-	C_4H_8
pentene	5	pent-	C_5H_{10}
hexene	6	hex-	C_6H_{12}

Table C11.04: Names and molecular formulae of the first five alkenes.

The presence of the carbon–carbon double bond in an alkene molecule makes alkenes much more reactive than alkanes (alkanes contain only carbon–carbon single bonds). Other atoms can add on to alkene molecules when the double bond breaks open. Under suitable conditions, molecules such as bromine, hydrogen and water (steam) will add across the carbon–carbon double bond. The reactivity of the alkenes makes them important for the synthesis of other organic molecules. The most important source of alkenes is from the **catalytic cracking** of long-chain alkanes from petroleum.

KEY WORDS

catalytic cracking: the decomposition of long-chain alkanes into alkenes and alkanes of lower relative molecular mass; involves passing the larger alkane molecules over a catalyst heated to 500 °C.

Chemical test for unsaturation

If an alkene, such as ethene, is shaken with a solution of bromine in water, the bromine loses its colour. Bromine has reacted with ethene in an addition reaction, producing a colourless compound (Figure C11.07b).

Alkanes are already fully saturated and cannot take part in addition reactions. An alkane would give no reaction with bromine water. The solution would stay orange–brown (Figure C11.07a).

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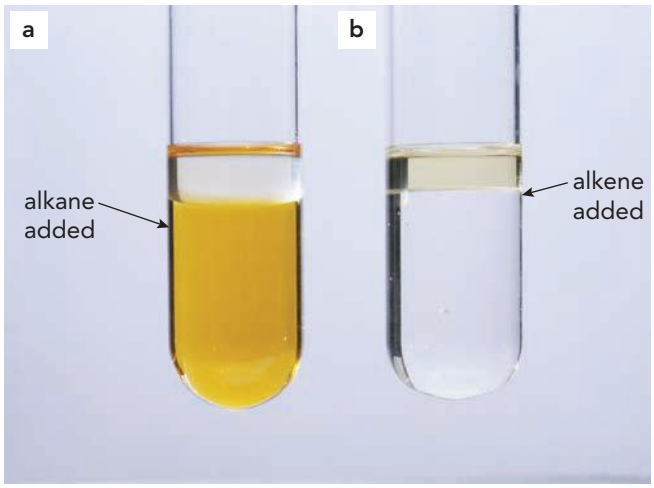

Figure C11.07: Test for unsaturation. Bromine water with **a:** an alkane and **b:** an alkene.

Questions

C11.01 Write down the names and molecular formulae of the first four alkanes.

C11.02 Draw the displayed formulae of methane and butane.

C11.03 The hydrocarbon propane is an important constituent of liquified petroleum gas (LPG). For the burning of propane in an excess of air, give:

a a word equation

b a balanced symbol equation.

C11.04 Draw a dot-and-cross diagram showing the arrangement of electrons in the bonding of ethene. Only show the outer (valency) electrons.

C11.05 What do you observe if ethene is bubbled through bromine water? Explain the difference between this observation and what would occur if ethane was bubbled through bromine water.

Catalytic cracking

The major source of hydrocarbons industrially is from refining oil. However, the demand for the various fractions does not necessarily match their supply from the **fractional distillation** process (Figure C11.08). For lighter fractions such as petrol, the demand is greater than the supply.

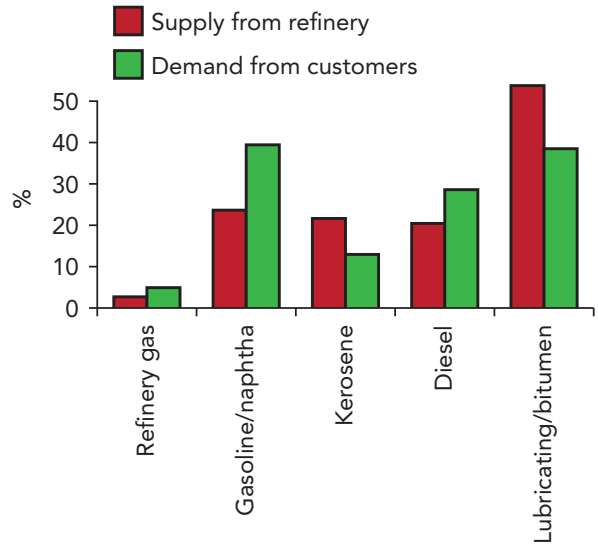

Figure C11.08: There is not the same economic demand for all the fractions from petroleum. The petroleum from different oilfields varies in composition so the values shown here are variable, but the general trend is true.

The opposite is true for heavier fractions such as kerosene (paraffin) and diesel oil (gas oil). Larger molecules from these heavier fractions can be broken into smaller, more valuable, molecules through catalytic cracking ('cat cracking').

Cracking takes place in a huge reactor (Figure C11.09). In this reactor, particles of catalyst (made of powdered minerals such as silica, alumina and zeolites) are mixed with the hydrocarbon fraction at a high temperature of around 500 °C. The cracked vapours containing smaller molecules are separated by distillation.

The shortened hydrocarbon molecules are produced by the following type of reaction:

$$\text{decane} \xrightarrow{\text{heat}} \text{octane} + \text{ethene}$$

$$C_{10}H_{22} \xrightarrow{\text{heat}} C_8H_{18} + C_2H_4$$

Figure C11.10 uses the displayed formulae to show the nature of the cracking reaction.

KEY WORDS

fractional distillation: a method of distillation using a fractionating column, used to separate liquids with different boiling points.

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Figure C11.09: A cracking plant in an oil refinery.

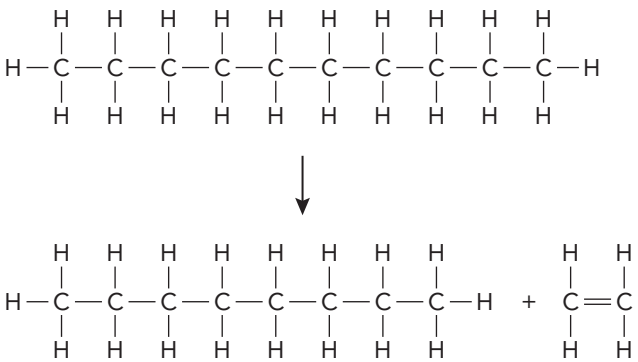

Figure C11.10: Cracking decane to produce octane and ethene.

This is just one of the possible reactions when decane is cracked. The molecules may not all break in the same place. The alkene fragment is not always ethene: propene and but-1-ene may also be produced. Some hydrogen is also broken off from the long-chain alkanes being cracked.

All cracking reactions give:

- an alkane with a shorter chain than the original and a short-chain alkene
- or two or more alkenes and hydrogen.

All the products of cracking are useful. The shortened alkanes can be blended with the gasoline fraction to enrich the petrol. The alkenes are useful as raw materials for making several important products such as polyethene.

The cracking reaction can be carried out in the laboratory using medicinal paraffin oil (Figure C11.11). The catalyst is heated strongly first and then the paraffin.

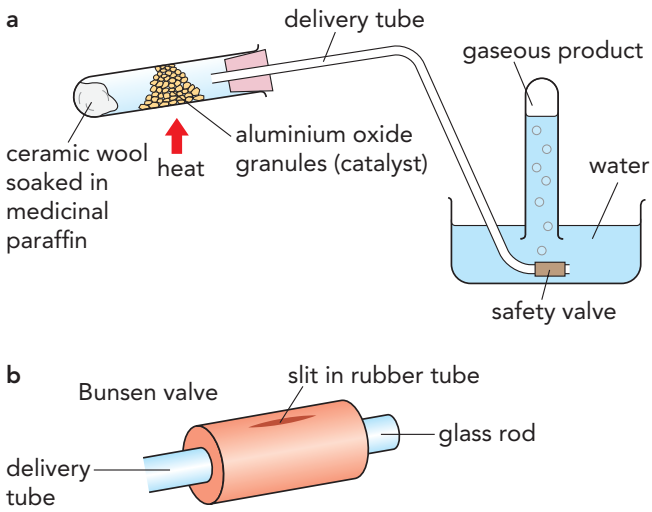

Figure C11.11 a: Cracking of a long-chain alkane in the laboratory. **b:** Use of a Bunsen safety valve to prevent 'suck back'.

The paraffin vapour passes over the catalyst that is kept hot. The gases produced in the cracking reaction can be collected in test-tubes. These gases can then be tested to see if they are alkenes using the bromine water test. For safety, the delivery tube can be fitted with a safety valve (Bunsen valve) to prevent cold water being drawn back into the hot apparatus.

Addition reactions

The presence of the carbon–carbon double bond in an alkene molecule makes these molecules much more reactive than alkanes (alkanes contain only carbon–carbon single bonds). Alkenes take part in addition reactions in which two substances react to form just one single product.

Bromination

The addition of bromine to an alkene can be carried out using a solution of the halogen in an organic solvent such as ethanol. In this case, the bromine atoms add across the double bond in the alkene. The double bond in ethene breaks open and forms new bonds to the bromine atoms (Figure C11.12). The red–brown colour of the bromine disappears during the reaction as the product in each case is colourless.

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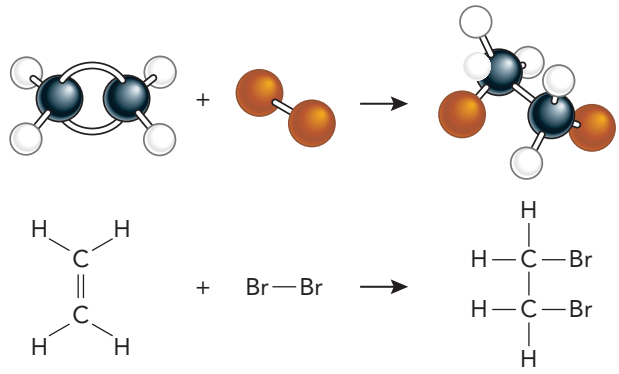
a ethene + bromine → 1,2-dibromoethane



b propene + bromine → 1,2-dibromopropane

$CH_3CH{=}CH_2 + Br_2 \rightarrow CH_3CHBrCH_2Br$

Figure C11.12: Bromination of **a:** ethene and **b:** propene.

This type of reaction, where a double bond breaks and adds two new atoms, is an addition reaction.

This is the colour change reaction shown previously as the test for unsaturation.

Hydrogenation

Hydrogen reacts with alkenes to form alkanes. The addition of hydrogen across a carbon–carbon double bond is known as **hydrogenation**. Ethene reacts with hydrogen if the heated gases are passed together over a nickel catalyst. The reaction produces ethane (Figure C11.13):

$$\text{ethene} + \text{hydrogen} \xrightarrow[\text{nickel}]{150\text{–}300\,^\circ\text{C}} \text{ethane}$$

$$CH_2{=}CH_2 + H_2 \rightarrow CH_3CH_3$$

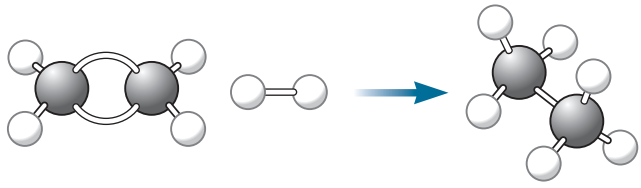


Figure C11.13: Hydrogenation of ethene.

Other alkenes also react in a similar way to produce the saturated alkane. Note that the isomers but-1-ene and but-2-ene both produce the same product on the addition of hydrogen.

$$\underset{\text{but-1-ene}}{CH_3CH_2CH{=}CH_2} + H_2 \rightarrow \underset{\text{butane}}{CH_3CH_2CH_2CH_3} \leftarrow H_2 + \underset{\text{but-2-ene}}{CH_3CH{=}CHCH_3}$$

KEY WORD

hydrogenation: an addition reaction in which hydrogen is added across the double bond in an alkene.

Hydrogenation reactions similar to the reaction with ethene are used in the manufacture of margarine from vegetable oils, such as corn oil and sunflower oil. These are edible oils and contain long-chain carboxylic acids. The hydrocarbon chains of these acids contain one or more carbon–carbon double bonds; they are unsaturated molecules (Figure C11.14).

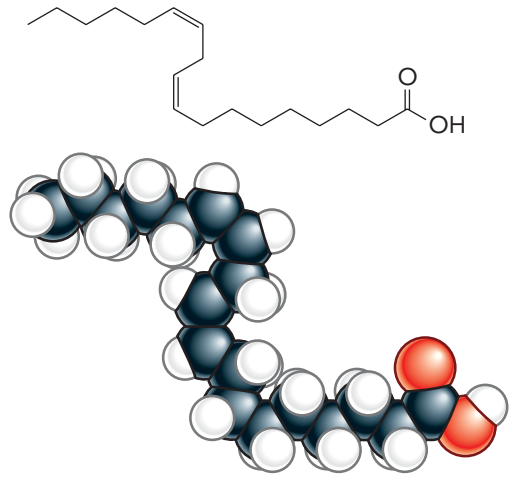


Figure C11.14: Sunflower oil and its products are rich in fats containing unsaturated molecules (note the carbon–carbon double bonds in the chain).

Hydrogen reacts with the vegetable oil when it passes over a nickel catalyst at about 60 °C. By hydrogenating some, but not all, of the carbon–carbon double bonds, the liquid vegetable oil can be made into a solid but spreadable fat (margarine).

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Catalytic addition of steam

Another important addition reaction is the reaction used in the manufacture of ethanol. Ethanol is an important industrial chemical and solvent. It is formed when a mixture of steam and ethene is passed over a catalyst of immobilised phosphoric(V) acid (the acid is adsorbed on silica pellets) at a temperature of 300 °C and a pressure of 6000 kPa:

$$\text{ethene} + \text{steam} \xrightarrow[\text{Phosphoric acid}]{300\,^\circ\text{C},\ 6000\ \text{kPa}} \text{ethanol}$$

$$C_2H_4(g) + H_2O(g) \rightarrow C_2H_5OH(g)$$

This **hydration** reaction produces ethanol of the high purity needed in industrial organic chemistry.

Other alkenes can be hydrated by similar reactions.

Care is needed in identifying the product when the carbon–carbon double bond is located at the end of the alkene molecule. Propene ($CH_3CH{=}CH_2$) and but-1-ene ($CH_3CH_2CH{=}CH_2$) give a mixture of products because the water molecule can add across the double bond in two different ways. Propene produces a mixture of propan-1-ol ($CH_3CH_2CH_2OH$) and propan-2-ol ($CH_3CH(OH)CH_3$). Propan-2-ol is the major product. But-1-ene also produces a mixture of two isomers as the product (Figure C11.15). In this case, butan-2-ol is the major isomer formed:

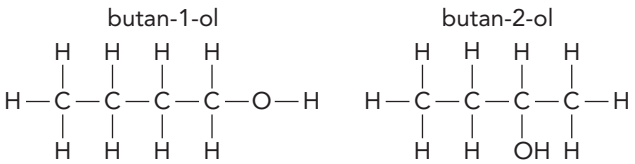

Figure C11.15: Products of hydration of but-1-ene. Butan-2-ol is the major product.

The hydration of but-2-ene produces just one product, butan-2-ol.

Questions

C11.06 What are the molecular and displayed formulae of 1,2-dibromoethane?

C11.07 One source of hydrogen for the Haber process to make ammonia is the catalytic cracking of ethane. Write the word and symbol equations for this reaction.

C11.08 Unsaturated hydrocarbons take part in addition reactions.

- **a** Write a word equation for the reaction between propene and hydrogen.
- **b** Write a symbol equation for the reaction between butene and steam.

Structural isomerism of hydrocarbons

The system of naming compounds emphasises the importance of molecular structure. Molecules with the same molecular formula can have different structures. Two members of the same homologous series can have the same number of atoms in their molecules, but these atoms can be connected together in different ways. Butane and 2-methylpropane have the same molecular formula (C_4H_{10}) but different structural formulae ($CH_3CH_2CH_2CH_3$ and $CH_3CH(CH_3)CH_3$, respectively). This is known as **structural isomerism**, and butane and 2-methylpropane are *structural isomers* of each other.

Structural isomerism can be shown by members of any homologous series and can arise from changing the position of the functional group in a molecule. In the alkenes, the two forms of butene (C_4H_8) are the first examples of this. The two isomers are but-1-ene and but-2-ene (Figure C11.16).

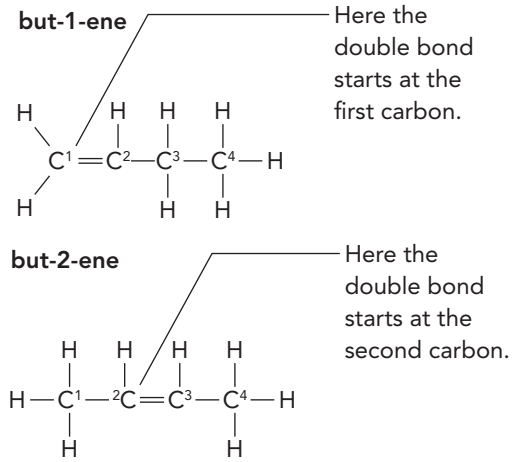

Figure C11.16: But-1-ene and but-2-ene are structural isomers of each other.

The structures in Figure C11.16 are different. This type of structural isomerism is also known as position isomerism.

KEY WORDS

hydration: the addition of the elements of water across a carbon–carbon double bond; H– adds to one carbon, and –OH to the other.

structural isomerism: a property of compounds that have the same molecular formula but different structural formulae; the individual compounds are known as *structural isomers*.

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Questions

C11.09 Give the structural formulae of the following compounds:

a propan-2-ol

b but-2-ene

C11.10 Define the term structural isomerism.

C11.11 Plot a graph of the boiling points of the first six alcohols (Table C11.05) against the number of carbon atoms in the molecule. Comment on the shape of the graph.

Name of alcohol	Boiling point / °C
methanol	65
ethanol	78
propan-1-ol	97
butan-1-ol	117
pentan-1-ol	137
hexan-1-ol	158

Table C11.05: Boiling points of the early members of the homologous series of alcohols.

C11.05 Alcohols

The alcohols are a homologous series of compounds with the –OH functional group and the general formula $C_nH_{2n+1}OH$. The simplest member of the series is methanol (CH_3OH). Methanol has one carbon atom per molecule and its covalent bonding was discussed in Chapter C2 (Figure C11.17).

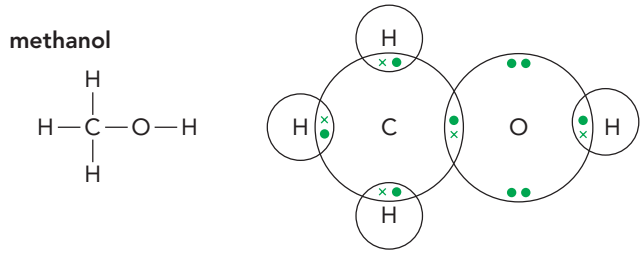

Figure C11.17: The displayed formula and bonding of methanol (CH_3OH).

The most important member of the alcohol series, however, is ethanol (C_2H_5OH). Ethanol is the second member of the series and has two carbon atoms in each molecule (Figure C11.18).

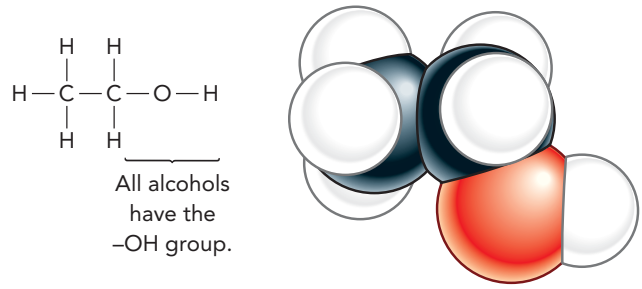

Figure C11.18: Displayed formula and model of ethanol (C_2H_5OH).

Note that the names of all the alcohols have the same ending (*-ol*). The early alcohols of the series are all neutral, colourless liquids that do not conduct electricity.

Uses of ethanol

Ethanol is an important solvent and a raw material for making other organic chemicals. Many everyday items use ethanol as a solvent. These include paints, glues, perfumes, aftershave and printing inks.

Ethanol undergoes complete combustion, burning with a clear flame, giving out a lot of heat:

ethanol + oxygen → carbon dioxide + water

$$C_2H_5OH(l) + 3O_2(g) \rightarrow 2CO_2(g) + 3H_2O(g)$$

On a small scale, ethanol can be used as methylated spirit (ethanol mixed with methanol or other compounds) in spirit lamps and stoves. However, ethanol is such a useful fuel that some countries have developed it as a fuel for cars, usually when blended with petrol.

Brazil was one of the first countries to produce ethanol fuel, in 1973. Ethanol produced by fermentation of sugar from sugar cane has been used as an alternative fuel to petrol or mixed with petrol (gasoline) to produce 'gasohol'. With a climate ideally suited for growing sugar cane, Brazil remains a world leader in ethanol fuel production (Figure C11.19).

Figure C11.19: An ethanol and petrol station in São Paulo, Brazil.

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Ethanol is a renewable resource and has the potential to reduce petroleum imports. Countries in Asia, Europe and the Americas have developed various blends of 'gasohol'. The most common is an E10 blend of 10% ethanol and 90% petrol. 'Gasohol' and other oxygenated fuels have the advantage of reducing the emissions of carbon monoxide from cars. With responsible development and control, biofuels have the potential to reduce future environmental pollution. However, issues of sustainability must be considered too. Land is needed to grow biofuel crops, so overuse of biofuels could encourage unsustainable levels of deforestation (Chapter C10).

ACTIVITY C11.01

The profile of a molecule

Ethanol (Figure C11.20) is a highly important organic compound with important industrial and social implications.

Figure C11.20: Ethanol: an important laboratory chemical and fuel.

In a group, produce an information leaflet that highlights and summarises these different aspects of ethanol. Include:

- a depiction of its molecular structure
- its usefulness as a fuel and solvent.

You may also wish to research the methods of industrial production.

Illustrate your leaflet with colourful images from magazines or downloaded from the internet.

When complete, come together as a class to compare leaflets and the different ways of illustrating the impact of this compound.

Peer assessment

Use the time you are in a group producing the poster on ethanol to question and challenge each other on the details of the structure, reactions and uses of ethanol. Include questions on how the compound fits into the general series of compounds known as the alcohols.

Questions

C11.12 What are the functional groups of the following homologous series?

- **a** alkenes
- **b** alcohols

C11.13 What is the:

- **a** molecular formula of ethene?
- **b** displayed formula of ethene?

C11.14 What are the correct names for the following straight-chain organic compounds?

- **a** C_4H_{10}
- **b** C_3H_6
- **c** C_3H_7OH

ACTIVITY C11.02

Organic flash cards

Organic chemistry involves several very specific words and definitions. In groups, get together to devise a set of flash cards to aid your understanding and help with revision.

The flash cards should have a question on the front of the card and the corresponding answer on the back of the card.

Questions covered could range from the following suggestions:

- What is a hydrocarbon?
- What is a homologous series?
- What are the formulae and structures of the different functional groups?

through to questions on specific structures:

- What is the displayed formula of propene?

Use different cards to put the questions from both directions (name → structure/structure → name).

Different groups could make cards covering different types of molecule and structure. Construct a set of cards and use them to quiz each other in the group. Then compare notes with the rest of the class to refine the content covered. You could also investigate the wide range of online software available for creating and using virtual flash cards.

Reflection

The naming and organisation of organic compounds and their molecules is, in many ways, highly systematic. How do you visualise the different types of compound and remember their differences? Could you develop a written approach to help you?

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C11.06 Fuels

Fossil fuels were formed in the Earth's crust from material that was once living. There are three major fossil fuels:

- **coal**
- **natural gas**
- **petroleum**.

These fossil fuels all contain hydrocarbons. Coal comes from fossil plant material. Petroleum (sometimes called crude oil) and natural gas are formed from the bodies of marine microorganisms. Methane is the main component of natural gas but petroleum is a complex mixture of many different hydrocarbons. The formation of these fuels took place over many millions of years. These fuels are therefore a **non-renewable (finite) resource**.

Formation of petroleum

Petroleum is one of the Earth's major natural resources, the result of a process that began up to 400 million years ago. When prehistoric marine creatures died, they sank to the seabed and were covered by mud. The change into petroleum and natural gas was brought about by high pressure, high temperature and bacteria acting over millions of years. The original organic material was broken down into hydrocarbons.

Geological movements and pressure created reservoirs of oil and gas. These reservoirs are not lakes of oil or pockets of gas. Instead, the oil or gas is spread throughout the pores in coarse rocks such as sandstone or limestone, in much the same way as water is held in a sponge. Oilfields and gas fields are detected by a series of geological and seismic surveys. Once a field is established, production oil rigs can be set up, on land or at sea (Figure C11.21).

Figure C11.21: An oil rig in the Caspian Sea.

Fractional distillation of petroleum

Petroleum is a mixture of many different hydrocarbon molecules. Most of the petroleum that is extracted from the ground is used to make fuel, but around 10% is used as a **chemical feedstock**, or raw material, in the chemical industry. Before the petroleum can be used, the various hydrocarbon molecules are separated by refining. This is done by fractional distillation at an oil refinery.

At a refinery, petroleum is separated into different groups of hydrocarbons that have different boiling points. These groups are known as **fractions**. These different boiling points are roughly related to the number of carbon atoms (chain length) in the hydrocarbons (Table C11.06).

Separation of the hydrocarbons takes place by fractional distillation using a **fractionating column** (or tower). At the start of the refining process, petroleum is preheated to a temperature of 350–400 °C and pumped in at the base of the tower. As it boils, the vapour passes up the tower.

KEY WORDS

coal: a black, solid fossil fuel formed underground over geological periods of time by conditions of high pressure and temperature acting on decayed vegetation.

natural gas: a fossil fuel formed underground over geological periods of time by conditions of high pressure and temperature acting on the remains of dead sea creatures; natural gas is more than 90% methane.

petroleum: a fossil fuel formed underground over many millions of years by conditions of high pressure and temperature acting on the remains of dead sea creatures.

non-renewable (finite) resources: sources of energy, such as fossil fuels, and other resources formed in the Earth over many millions of years, which we are now using up at a rapid rate and cannot replace.

chemical feedstock: a chemical element or compound which can be used as a raw material for an industrial process making useful chemical products.

fractions (from distillation): the different mixtures that distil over at different temperatures during fractional distillation.

fractionating column: the vertical column that is used to bring about the separation of liquids in fractional distillation.

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Fraction	Approximate number of carbon atoms in hydrocarbons		Approximate boiling range / °C	
refinery gas	1–4	C_1–C_4	below 25	chain length and boiling point decrease from the bottom to the top of the fractionating column
petrol (gasoline)	4–12	C_4–C_{12}	40–100	
naphtha	7–14	C_7–C_{14}	90–150	
kerosene (paraffin)	12–16	C_{12}–C_{16}	150–240	
diesel oil (gas oil)	14–18	C_{14}–C_{18}	220–300	
fuel oil	19–25	C_{19}–C_{25}	250–320	
lubricating fraction	20–40	C_{20}–C_{40}	300–350	
bitumen	over 70	$>C_{70}$	above 350	

Table C11.06: Various petroleum fractions (note the different terms used in different parts of the world for the same fraction).

It passes through a series of bubble caps, and cools as it rises further up the column. The different fractions cool and condense at different temperatures, and therefore at different heights in the column. The fractions condensing at the different levels are collected on trays. Fractions from the top of the tower are called 'light' and those from the bottom are called 'heavy'. Each fraction contains a number of different hydrocarbons.

The individual single hydrocarbons can then be obtained by further distillation. Figure C11.22 shows the separation into different fractions and some of their uses.

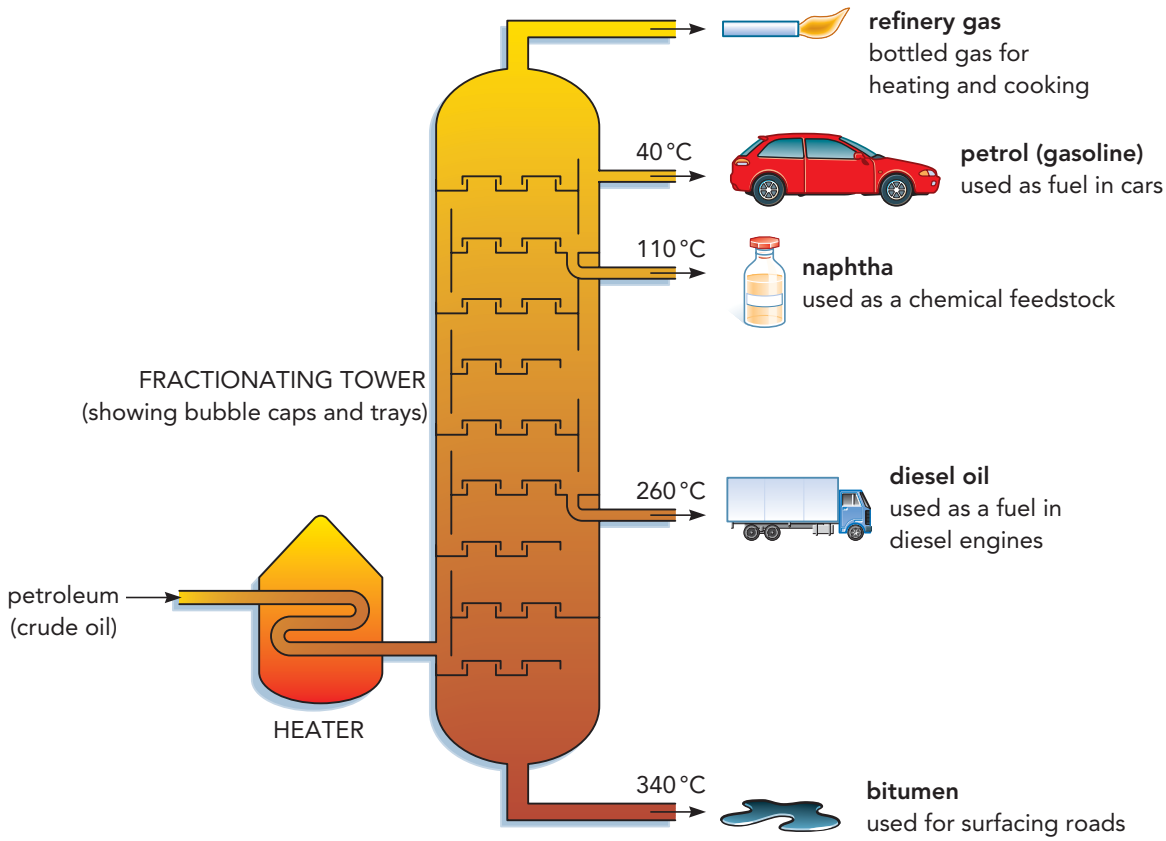

Figure C11.22: Fractional distillation of petroleum in a refinery.

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Questions

C11.15 State a use for the following fractions from the distillation of petroleum (crude oil): bitumen, diesel, naphtha and gasoline.

C11.16 Put the following fractions in order of increasing boiling point: diesel, petrol, refinery gas, bitumen, naphtha.

ACTIVITY C11.03

Refined sudoku

Work in pairs. The aim is to devise and use this logic puzzle to help you learn, and test each other on, the different fractions produced from the distillation of petroleum. Many of you will have solved these puzzles with the numbers 1 to 9.

Here we are creating our puzzle using the names of the fractions from the distillation of petroleum and, because we need nine items, another related fossil fuel, natural gas (Table C11.07).

Alternatively, you can set up a puzzle using the uses of the fractions (the right-hand column).

The puzzle is based on a grid and you need to work out the contents of the blank squares (Table C11.08). The rules for filling in the grid are:

- no entry into the horizontal squares can be repeated
- no entry in the vertical squares can be repeated
- there can be no repeat entries in each of the 3 × 3 boxes in the grid.

Table C11.08 is an example set up for you to try. Copy and complete the puzzle using the names of the fractions.

natural gas	methane gas
refinery gas	heating/cooking
gasoline	fuel – cars
naphtha	chemical feedstock
diesel oil	diesel engines
lubricating oil	lubricants
bitumen	roads

Table C11.07: Fossil fuel products and their uses.

bitumen	natural gas	refinery gas	lubricating oil	gasoline				
		gasoline	bitumen			lubricating oil		
lubricating oil								bitumen
		natural gas		refinery gas				
gasoline								naphtha
				lubricating oil	naphtha			
diesel oil								natural gas
refinery gas		lubricating oil			natural gas			
			diesel oil		refinery gas	naphtha	bitumen	lubricating oil

Table C11.08: A sudoku puzzle grid using the petroleum refinery fractions.

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CONTINUED

When you have completed the first puzzle, each use a blank grid to set up a puzzle for your partner to try. You can use the fraction names again, or the uses. You can change the difficulty by altering the number of squares you fill in at the start (Table C11.08 has 32 spaces filled; a harder puzzle could have as few as 28 filled spaces).

While working on the puzzle, discuss with your partner the basis of the separation that gives these different fractions:

- Which fractions have the highest boiling points?
- How do properties such as the chain length of the molecules and the viscosity of the fractions vary between the fractions?

A third column of data, such as the length of the carbon chains in the fractions, could be included in the puzzle. Would it be useful for you to set up a puzzle based on those data?

Peer assessment

Once you have completed the puzzle and finished your discussion, use the following checklist to peer assess:

My partner …

- discussed which fractions had the highest boiling point
- could explain how the chain length of molecules vary
- could explain how the viscosity of the fractions vary.

Is there anything your partner could do to improve their knowledge on this topic?

C11.07 Polymers

All living things contain **polymers**. **Proteins**, carbohydrates, wood and natural rubber are all polymers. Synthetic polymers, often called plastics, are to be found everywhere in modern technological societies, ranging from car and aircraft components to packaging and clothing.

Polymers are large organic molecules. They are made up of many small repeating units known as **monomers** (Figure C11.23) joined together by **polymerisation**. These units are repeated any number of times from about a hundred to more than a million.

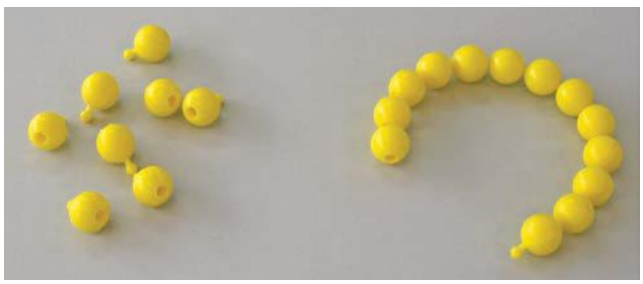

Figure C11.23: Making a chain of beads is similar to joining monomers together to make a polymer.

Some polymers are homopolymers, containing just one monomer. Poly(ethene), poly(propene) and poly(chloroethene) are three examples of homopolymers. Other polymers are copolymers. These are made of two or more different types of monomer. For example, nylon is made from two different monomers and biological proteins are made from up to 20 different monomers (**amino acids**).

KEY WORDS

polymer: a substance consisting of very large molecules made by polymerising a large number of repeating units, or monomers.

proteins: polymers of amino acids formed by a condensation reaction; they have a wide variety of biological functions.

monomer: a small molecule, such as ethene, which can be polymerised to make a polymer.

polymerisation: the chemical reaction in which molecules (monomers) join together to form a long-chain polymer.

amino acids: naturally occurring organic compounds that possess both an amino ($–NH_2$) group and an acid (–COOH) group in the molecule; there are 20 naturally occurring amino acids and they are polymerised in cells to make proteins.

Addition polymerisation

The alkene fragments from the catalytic cracking of petroleum fractions were the starting monomers for the first plastics. Alkenes such as ethene contain a carbon–carbon double bond. These molecules can take part in addition reactions where the double bond is broken and other atoms attach to the carbons. The double bond in ethene enables many molecules of ethene to join to each other to form a large molecule called poly(ethene) (Figure C11.24).
Note that when you draw out a section of the polymer chain, you must show the open continuation bonds at the end of the section.

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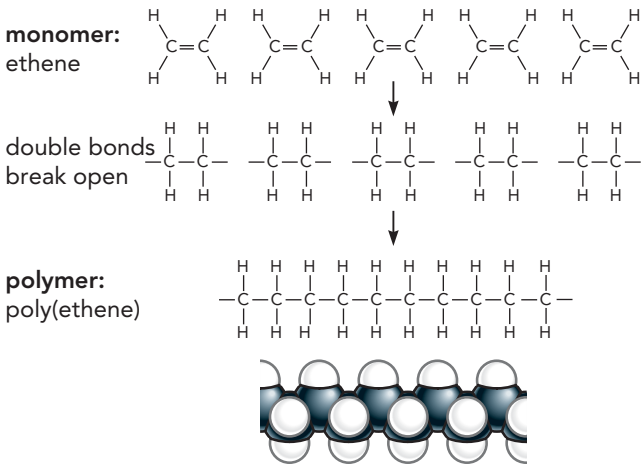

Figure C11.24: The polymerisation of ethene produces poly(ethene).

Various conditions can be used to produce different types of poly(ethene). Generally, a high pressure, a temperature at or above room temperature and a catalyst are needed. The reaction can be summarised by the equation shown in Figure C11.25, where *n* is a very large number.

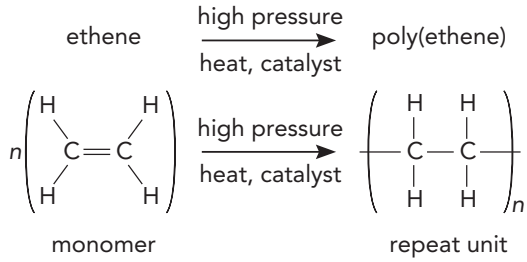

Figure C11.25: Polymerisation of ethene; a very large number of monomers (*n*) are joined together.

Here we can see the monomer, ethene, and the polymer, poly(ethene), represented by the repeat unit, i.e. the unit within the polymer that is repeated. The repeat unit is shown in brackets with the end bonds sticking out to show how the repeat units connect to each other. The '*n*' outside the brackets is to show us that there is a large number of the repeat unit within the polymer chain.

Other alkene molecules can also produce **addition polymers**. Propene will polymerise to produce poly(propene).

KEY WORDS

addition polymer: a polymer formed by an addition reaction – the monomer molecules contain a carbon–carbon double bond.

As we saw earlier for the polymerisation of ethene, the reaction to form poly(propene) can be summarised by the equation in Figure C11.26.

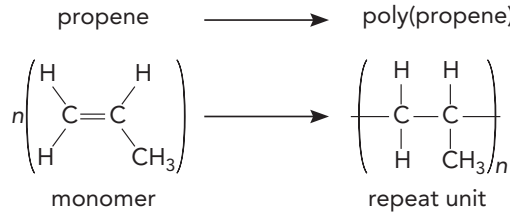

Figure C11.26: The polymerisation of propene monomers to form poly(propene).

The long-chain molecule of poly(propene) is similar in structure to poly(ethene) but with a methyl ($-CH_3$) group attached to every other carbon atom in the chain (Figure C11.26).

The equations that summarise the formation of poly(chloroethene) (PVC) and poly(tetrafluoroethene) (PTFE) are shown in Figure C11.27.

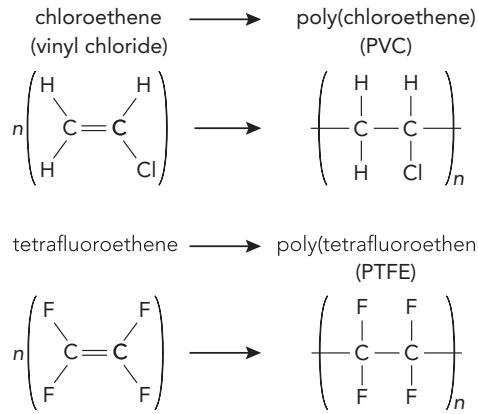

Figure C11.27: The equations for the formation of PVC and PTFE.

You can see from this discussion that there are different ways to represent the formation and structure of an addition polymer. Table C11.09 illustrates how to represent the structure of the polymer formed from a given monomer, and also the reverse process of deducing the monomer used from the structure of the polymer.

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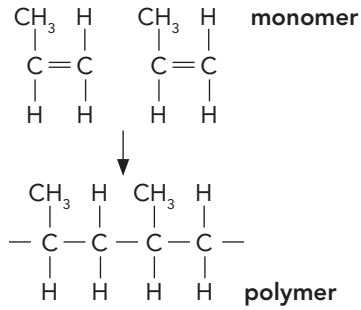
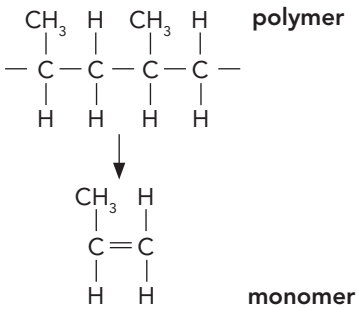
From monomer to polymer	From polymer to monomer
• draw the monomers with their double bonds next to each other • remove the double bonds and draw single bonds in the space between the monomers	• identify the repeating unit – it will have two carbon atoms with a single bond between them; put a bracket round it • draw that unit as a separate molecule with a double bond in it
	

Table C11.09: How to deduce the relationship between monomer and addition polymer.

The main features of addition polymers can be summarised as follows:

- all polymers are long-chain molecules made by joining together a large number of monomer molecules
- addition polymerisation involves monomer molecules that contain a carbon–carbon double bond
- addition polymers are homopolymers, made from a single monomer
- during addition, the double bonds open up and the monomer molecules join together to make a molecule with a very long chain (remember to put in the *n* when representing the structure).

Questions

C11.17 State what is meant by addition polymerisation and give an equation for the formation of poly(ethene) from ethene.

C11.18 Draw the structure of the repeating unit in the following polymers:

a poly(propene)

b poly(chloroethene) (PVC)

C11.19 **a** What common bonding feature must all monomers, whether substituted or not, contain?

b Draw the structure of the addition polymer made from styrene monomers (show at least three repeating units in your structure).

Condensation polymerisation

A condensation polymer is one that is formed when a **condensation reaction** takes place between the monomers to join them together in the polymer chain. A condensation reaction is one in which two molecules react together to form a new, larger molecule with the elimination of a small molecule, usually water. We will now consider one example of a condensation polymer: nylon, a **polyamide**.

KEY WORDS

condensation reaction: a reaction where two or more substances combine together to make a larger compound, and a small molecule is eliminated (given off).

polyamide: a polymer where the monomer units are joined together by amide (peptide) links, e.g. nylon and proteins.

Nylon (a polyamide)

In the early 1930s, the American company DuPont was conducting research into artificial fibres. Knowledge of silk and wool gave clues as to how protein molecules are built. Wallace Carothers, the leader of organic chemistry at DuPont, imitated the linkage in proteins and produced the first synthetic fibre, 'nylon'. Nylon is a solid when first formed, but it can then be melted and forced through small holes. The long filaments cool, and the fibres produced are stretched to align the polymer molecules and then dried.

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The fibres can be woven into fabric to make shirts, ties, sheets and so on, or turned into ropes, nets (Figure C11.28) or racket strings. However, nylon is not just made into fibres. It has proved to be a very versatile material and can be moulded into strong plastic items such as gearwheels.

Figure C11.28: Nylon fishing nets.

Nylon is a copolymer of two different monomers, a diamine and a dicarboxylic acid (Figure C11.29). Each monomer consists of a chain of carbon atoms (which are shown here simplified as blocks). At both ends of the monomers are functional groups. An amine group ($–NH_2$) on the first monomer reacts with a carboxylic acid group (–COOH) on the second monomer to make a link between the two molecules. Each time a link is made, a water molecule is lost.

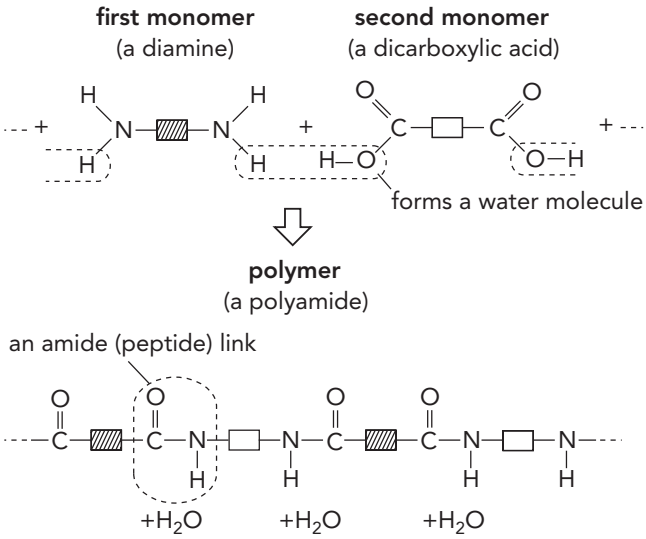

Figure C11.29: The formation of a polyamide (nylon) by condensation polymerisation.

As a result, this type of polymer is known as a **condensation polymer**. Because an **amide link (or peptide link)** is formed during condensation polymerisation, nylon is known as a polyamide.

Take careful note of the structure of the two monomers used to make the synthetic polyamide, nylon (Figure C11.29). The fact that each has the same functional group at either end of the molecule results in an important feature of the polymer produced. This feature is that the direction of each amide link is the opposite of the two link regions immediately on either side of it. It is important to remember this when drawing the structure of a section of the nylon chain (see Figure C11.29). In nylon, the repeat unit is the smallest section of the polymer which can be repeated to give the entire polymer. In a copolymer, this will always include both monomers. Again, this is written in brackets with an '*n*' outside to represent the large number of repeat units present.

KEY WORDS

condensation polymer: a polymer formed by a condensation reaction, e.g. nylon is produced by the condensation reaction between 1,6-diaminohexane and hexanedioic acid; this is the type of polymerisation used in biological systems to produce proteins, nucleic acids and polysaccharides.

amide link (or peptide link): the link between monomers in a protein or nylon, formed by a condensation reaction between a carboxylic acid group on one monomer and an amine group on the next monomer.

Comparing addition and condensation polymerisation

Some very useful synthetic polymers have been made by the two types of polymerisation. Both methods take small molecules and make long repeating chains from them. However, there are differences between the two methods. These are summarised in Table C11.10.

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	Addition polymerisation	Condensation polymerisation
monomers used	usually many molecules of a single monomer	molecules of two monomers usually used
	monomer is unsaturated, usually contains a carbon–carbon double bond	monomers contain reactive functional groups at ends of each molecule
reaction taking place	an addition reaction; monomers join together by opening the carbon–carbon double bond	condensation reaction with loss of a small molecule (usually water) each time a monomer joins the chain
nature of product	only a single product – the polymer	two products – the polymer plus water (or some other small molecule)
	non-biodegradable	can be biodegradable (nylon takes 40–50 years)
	resistant to acids	PET can be hydrolysed back to monomers by acids or alkalis

Table C11.10: A comparison of the processes of making synthetic polymers.

Questions

C11.20 **a** What are the essential features of condensation polymerisation?

b Name *one* artificial condensation polymer, and state the type of linkage present.

C11.21 Nylon is a synthetic polymer that is held together by the same linkage as protein molecules.

Draw a diagram of the structure of nylon (the structure of the centre of the monomer is not required and can be represented as a block).

PROJECT C11.01 CHARTING LINKED REACTIONS

When studying the different types of reaction that a compound, or group of compounds, can take part in, it is often useful to draw a reaction summary. Figure C11.30 shows such a chart for the characteristic reactions of acids.

Working in a group, use a large sheet of paper to create a similar chart for an alkene of your choice. In your class, make sure each group is creating a chart for a different alkene.

Include as many reactions as you can.

Once all groups have finished, explain your chart to the rest of the class. Make notes while other groups are explaining their alkene reaction chart.

Working together as a class, can you link all the charts together to make one global chart for all the reactions covered in this chapter?

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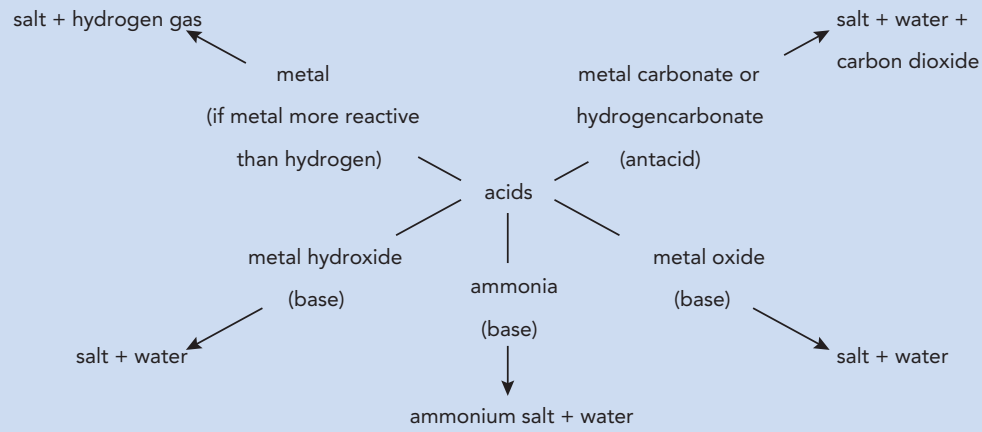

Figure C11.30: Chart of the reactions of acids.

Reflection

Did drawing up the chart help you understand the relationships of ideas within the topic?

SUMMARY

Different organic compounds can be distinguished from each other by their molecular and displayed formulae.
Homologous series of organic compounds (e.g. alkanes or alkenes) have the same general formula and similar chemical properties because they contain the same functional group.
The general characteristics of a homologous series include increasing chain length, similar chemical properties and related trends in physical properties.
Alkanes are a homologous series of saturated hydrocarbons as all the carbon–carbon bonds are single covalent bonds.
Compounds containing at least one carbon–carbon double or triple bond are said to be unsaturated (e.g. alkenes are unsaturated as they contain a carbon–carbon double bond).
The alkanes are a generally unreactive series of hydrocarbons that burn readily and are used as fuels.
Alkenes can be obtained from the catalytic cracking of long-chain alkane molecules present in the fractions obtained from the fractional distillation of petroleum.
Alkenes are more reactive than alkanes and take part in addition reactions with bromine, hydrogen and steam.
Structural and displayed formulae can be drawn to represent the bonding in the different molecules.

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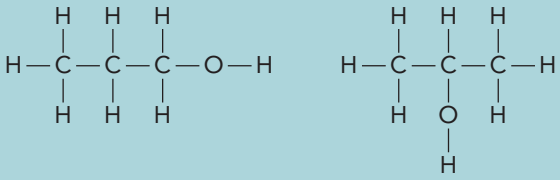
CONTINUED

Alcohols are another example of a homologous series. They are used as fuels and solvents.
The major fossil fuels are coal, natural gas and petroleum. Methane is the main constituent of natural gas and petroleum is a mixture of hydrocarbons.
Fractional distillation can be used to separate petroleum into a range of useful fractions.
The fractions from the distillation of petroleum each have distinctive uses.
The fractions obtained from fractional distillation progressively vary in chain length and boiling point.
Polymers are long-chain molecules built up from a large number of monomer molecules, with poly(ethene) as an example of the addition polymerisation of ethene monomers.
The structure of an addition polymer or its repeat unit can be identified from the formula of a given alkene.
Polymers can also be formed by condensation reactions, for example the polyamide nylon.
The structure of a condensation polymer or its repeat unit can be identified from given monomers.
Addition and condensation polymers depend on different types of monomers, linkage regions and means of formation.

PRACTICE QUESTIONS

1 The two compounds whose structures are shown in the figure have similar chemical properties.



Identify the reason for this.

A Their molecules have the same relative molecular mass.

B Their molecules have the same functional group.

C Their molecules have the same number of oxygen atoms.

D Their molecules have the same number of carbon atoms. **[1]**

COMMAND WORD

identify: name/select/recognise.

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CONTINUED

2 Organic compounds have names that correspond to the homologous series they belong to. Three types of organic compound have names ending in *-ane, -ene,* or *-ol*. Identify how many of these types of compound contain oxygen.

A three

B two

C one **[1]**

3 Ethane and ethene are both hydrocarbon gases.

a **Suggest** what the term 'hydrocarbon' means. **[1]**

b Bromine water can be used to distinguish between the two gases. **State** the result that would be seen if ethane was bubbled through bromine water. **[1]**

c Ethene reacts with steam to produce ethanol. **Outline** the conditions needed to make this reaction happen. **[2]**

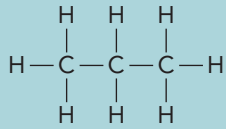
d **Give** *two* uses of ethanol. **[2]**

e Ethene is used as a monomer in the formation of poly(ethene). Give the process by which poly(ethene) is made. **[1]**

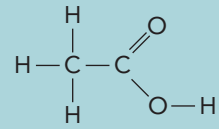
[Total: 7]

4 The displayed formulae of five organic compounds **A–E** are shown in the figure.

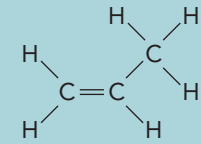
A



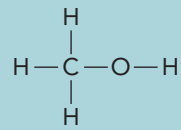
B



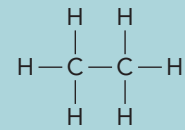
C



D



E



a State which compound **A–E** is an alkene. **[1]**

b State which *two* compounds **A–E** belong to the same homologous series. **[2]**

c State the functional group in the alkene homologous series. **[1]**

d Alkenes are referred to as unsaturated compounds. **Describe** what is meant by the term unsaturated. **[1]**

e State the molecular formula for compound C. **[1]**

[Total: 6]

COMMAND WORDS

suggest: apply knowledge and understanding to situations where there is a range of valid responses in order to make proposals/put forward considerations.

state: express in clear terms.

outline: set out the main points.

give: produce an answer from a given source or recall/memory.

COMMAND WORD

describe: state the points of a topic/give characteristics and main features.

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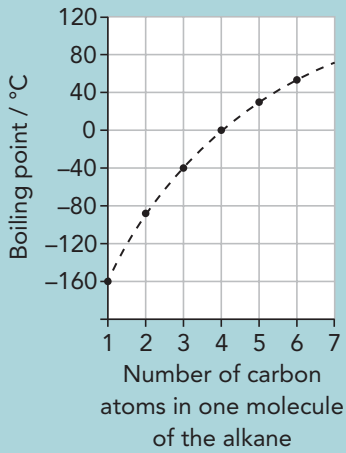
5 One feature of a homologous series is that there is a regular change in the values of certain physical properties. The graph shows the way in which the boiling points of some alkanes depend on the number of carbon atoms in their molecules.



From the graph, **deduce** the boiling point of propane. **[1]**

6 Some of the fractions separated from petroleum are listed here:

bitumen
kerosene
petrol (gasoline)
refinery gas

a Identify the fraction that is *not* used as a fuel. **[1]**

b Identify the fraction with the highest boiling point. **[1]**

c Identify the fraction that is used to power motor vehicles. **[1]**

[Total: 3]

7 **a** Petroleum is a mixture of compounds composed of hydrogen and carbon only. What do we call these compounds? **[1]**

b Petroleum can be separated into fractions by fractional distillation. State the physical properties of the compounds in each fraction that make this separation possible. **[1]**

c State the main use of the kerosene fraction. **[1]**

d The heavier fractions are sometimes cracked to form alkenes.

i Describe the conditions needed for this process. **[2]**

ii Give the name of the product formed during cracking which is not a hydrocarbon. **[1]**

e A long-chain molecule from petroleum was cracked to form two different alkenes.

Complete the equation.

$C_{10}H_{22} \rightarrow C_4H_8 + 2\_\_\_\_ + \_\_\_\_$ **[2]**

[Total: 8]

COMMAND WORD

deduce: conclude from available information.

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SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
draw and interpret displayed formulae	C11.01			
understand that unsaturated compounds contain carbon–carbon double bonds and saturated compounds contain carbon–carbon single bonds	C11.01			
understand that a homologous series is a family of compounds with the same general formula and similar chemical properties because they contain the same functional group	C11.01			
describe the general characteristics of a homologous series, including increasing chain length, similar chemical properties and related trends in physical properties	C11.01			
distinguish the different organic compounds by their molecular and displayed formulae	C11.02			
understand how to write the structural formulae of molecules from the different homologous series, including the alkanes, alkenes and alcohols	C11.02			
understand how to draw the structural and displayed formulae of unbranched members of different homologous series containing up to four carbon atoms, including alkanes, alkenes and alcohols	C11.02			
state that the alkanes are a series of saturated hydrocarbons as all the carbon–carbon bonds are single covalent bonds	C11.03			
describe alkanes as a series of generally unreactive hydrocarbons that are used as fuels	C11.03			
understand that alkenes contain at least one carbon–carbon double bond and are unsaturated molecules	C11.04			
describe the test to distinguish unsaturated and saturated molecules using bromine water	C11.04			
describe how alkenes are obtained from long-chain alkanes present in fractions obtained from the distillation of petroleum	C11.04			
describe how alkenes take part in addition reactions with bromine, hydrogen and steam.	C11.04			

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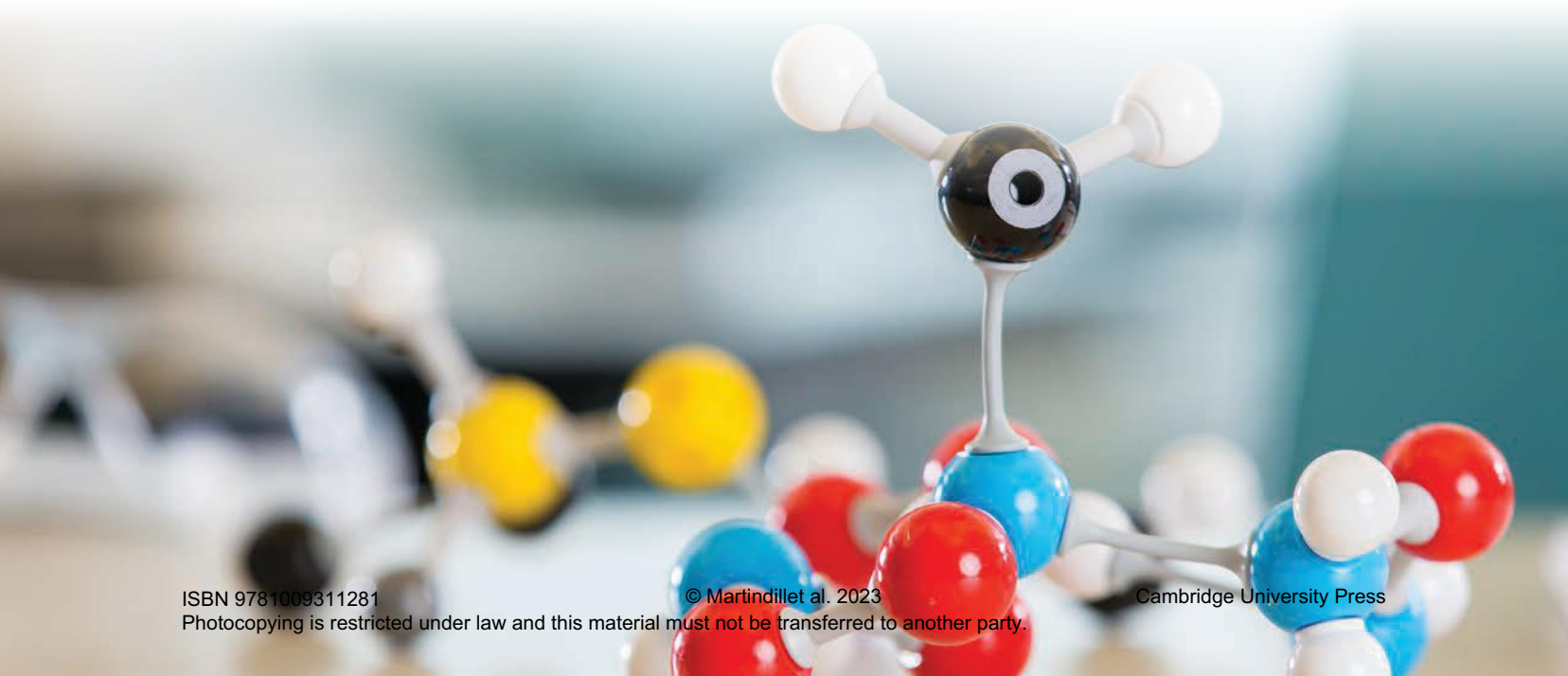
I can	See topic . . .	Needs more work	Almost there	Confident to move on
describe alcohols as another example of a homologous series which are used as fuels and solvents	C11.05			
name the major fossil fuels as coal, natural gas and petroleum, with methane the main constituent of natural gas and petroleum being a mixture of hydrocarbons	C11.06			
describe how petroleum can be separated into useful fractions by fractional distillation	C11.06			
understand that these fractions vary progressively in chain length and boiling point	C11.06			
describe how each different fraction from the distillation has its distinctive uses	C11.06			
define polymers as long-chain molecules built up from large numbers of monomer molecules, with poly(ethene) as an example of addition polymerisation of ethene monomers	C11.07			
identify the structure of an addition polymer or its repeating unit from the formula of a given alkene	C11.07			
understand that polymers can also be formed by condensation reactions, e.g. polyamides (nylon)	C11.07			
describe and draw the structure of the condensation polymer nylon	C11.07			
describe the differences between addition and condensation polymerisation.	C11.07			



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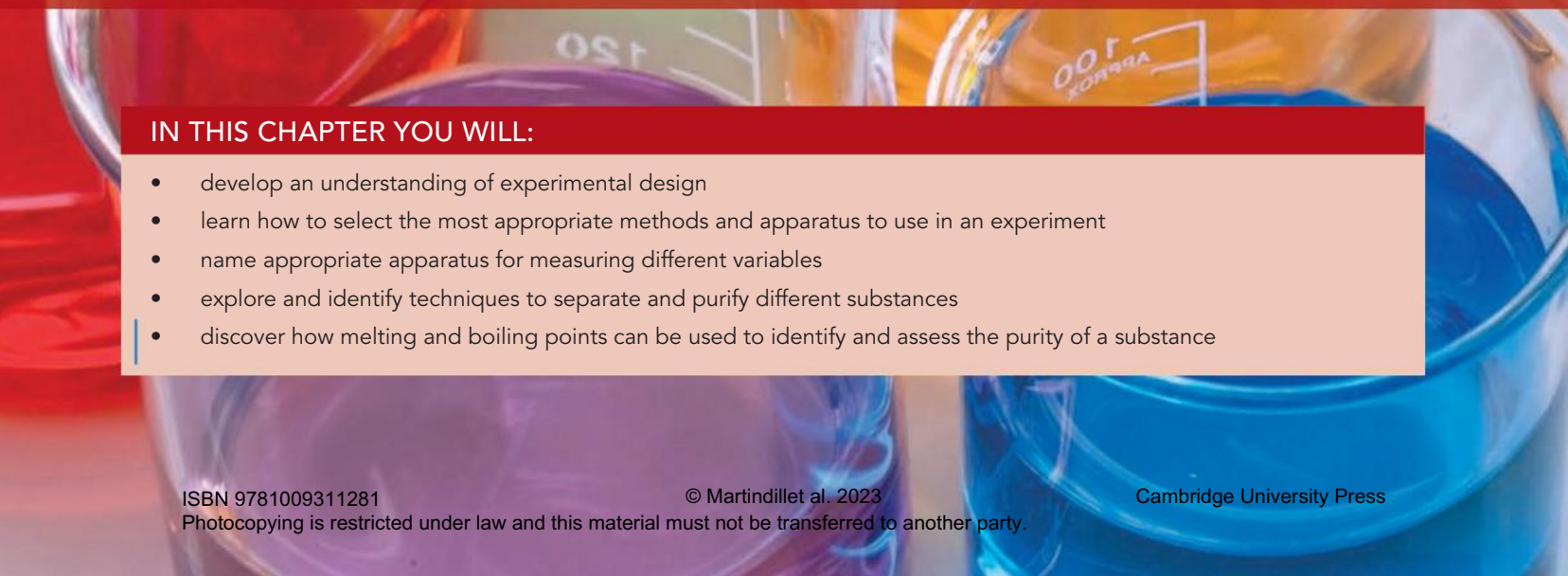
C12

Experimental techniques and chemical analysis

All learners study some content in this chapter



IN THIS CHAPTER YOU WILL:

- develop an understanding of experimental design
- learn how to select the most appropriate methods and apparatus to use in an experiment
- name appropriate apparatus for measuring different variables
- explore and identify techniques to separate and purify different substances
- discover how melting and boiling points can be used to identify and assess the purity of a substance

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- describe how chromatography can be used to separate mixtures of soluble coloured substances
- state and use the equation to determine the R_f value
- learn how characteristic colours produced by flame tests can be used to identify metal cations
- explore how precipitation reactions with solutions of sodium hydroxide and ammonia can be used to identify aqueous cations
- discover how chemical analysis is used to determine the presence of anions
- develop simple practical techniques for proving the identity of different gases
- describe acid–base titration as a form of quantitative analysis
- learn how to identify the end-point of a titration using an indicator.

BEFORE YOU START

Chemists need to be able to design experiments carefully and safely. Work in groups of three of four to consider the scenario below and discuss the questions that follow.

You have been asked to plan an experiment to analyse how temperature affects the rate at which a new drug can be produced. The drug is produced as a white precipitate (insoluble salt) when solutions of two chemicals A and B are mixed together.

1 What should you include as you plan your experiment?
2 Can you think of any general hazards that would need to be taken into consideration?
3 How would you reduce any risk?
4 What measurements would you need to make?

SCIENCE IN CONTEXT C12.01

Safe drinking water for all

Safe drinking water is considered a basic human right by the United Nations. Many people take access to clean drinking water for granted. However, it is estimated that around 800 million people lack even a basic drinking-water service. The problems are being compounded with growing populations and the pressures caused by climate change increasing the demand for clean water. Traditional supplies such as reservoirs and wells cannot meet the demand and so research has focused on alternative methods to provide clean water. Many of these approaches are based on simple separation techniques.

For small-scale production it is possible to distil water. This approach involves boiling and then condensing the water. It is therefore energy intensive, and if fossil fuel is used it is also unsustainable. This problem can be overcome by using small solar-powered distillation units. The stills are simple black-bottomed containers filled with water and covered with clear glass or plastic. Sunlight is absorbed by the black material and increases the rate of evaporation. The evaporated water is trapped by the clear cover and funnelled away. Most pollutants do not evaporate and remain in the container. The stills are usually used in remote areas with limited freshwater. However, they only produce small volumes of water and require access to sunlight.

Figure C12.01: Chemists working in a laboratory at a desalination plant in Oman.

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An alternative, larger-scale approach is **desalination**. This method removes salt and other minerals from water using distillation or membrane filtration (reverse osmosis). Desalination is energy intensive and has an environmental impact as the toxic brine produced can damage coastal and marine ecosystems. The process works well for countries with limited freshwater but with access to seawater. The Middle East has most of the world's desalination capacity, with Oman producing nearly 90% of its drinking water from desalination (Figure C12.01).

A novel approach to supplying clean water is to use mini personal water filtration systems ('filter straws') to drink directly from natural water sources. The filter straws contain many hollow fibre micro-tubes that trap contaminants while allowing clean water to pass through. The straws are highly effective at removing small particles of mud and sand and they also filter out harmful microbes.

Discussion questions

1 What are the strengths and weaknesses of using portable distillation units and desalination to produce drinking water?

2 What does the filter straw need to be able to remove from the water? Would you drink untreated river water using one of these straws?

C12.01 Experimental design

There are several steps to consider when planning an experimental investigation (Figure C12.02).

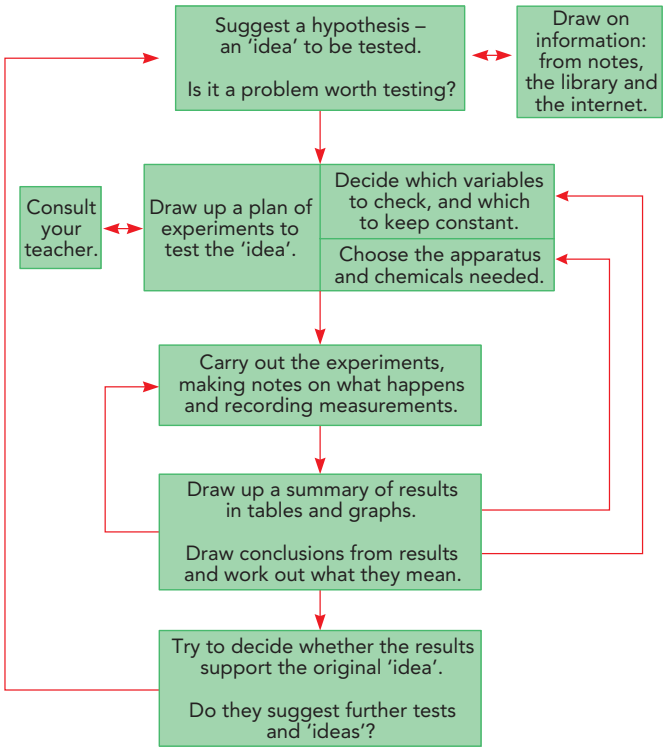

Figure C12.02: Steps involved in planning an experimental investigation.

Selecting the correct apparatus

The choice of apparatus requires careful thought. It is also necessary to consider the level of accuracy, how to control variables, sources of error and any steps to minimise safety concerns.

At the design stage you should plan which equipment to use and write a method detailing how to use it.

The type of apparatus used in an experiment will depend on the scale and the **accuracy** of the results required. The scale of an experiment is a measure of the amount of product needed. A small-scale experiment as carried out in a laboratory may produce milligram or gram amounts of a product, whereas large-scale experiments of the type used in industry will produce many tonnes of material. The accuracy is a measure of how close a result is to its true value. The apparatus chosen for an experiment should give results with high **precision** (results that are close to each other).

You need to be able to identify common pieces of laboratory equipment (Figure C12.03). You should be aware of the purpose and accuracy of the apparatus.

KEY WORDS

desalination: the removal of dissolved salts and minerals from seawater to produce drinking water.

accuracy: how close a value is to the true value.

precision: the degree to which repeat measurements are consistent (close to each other).

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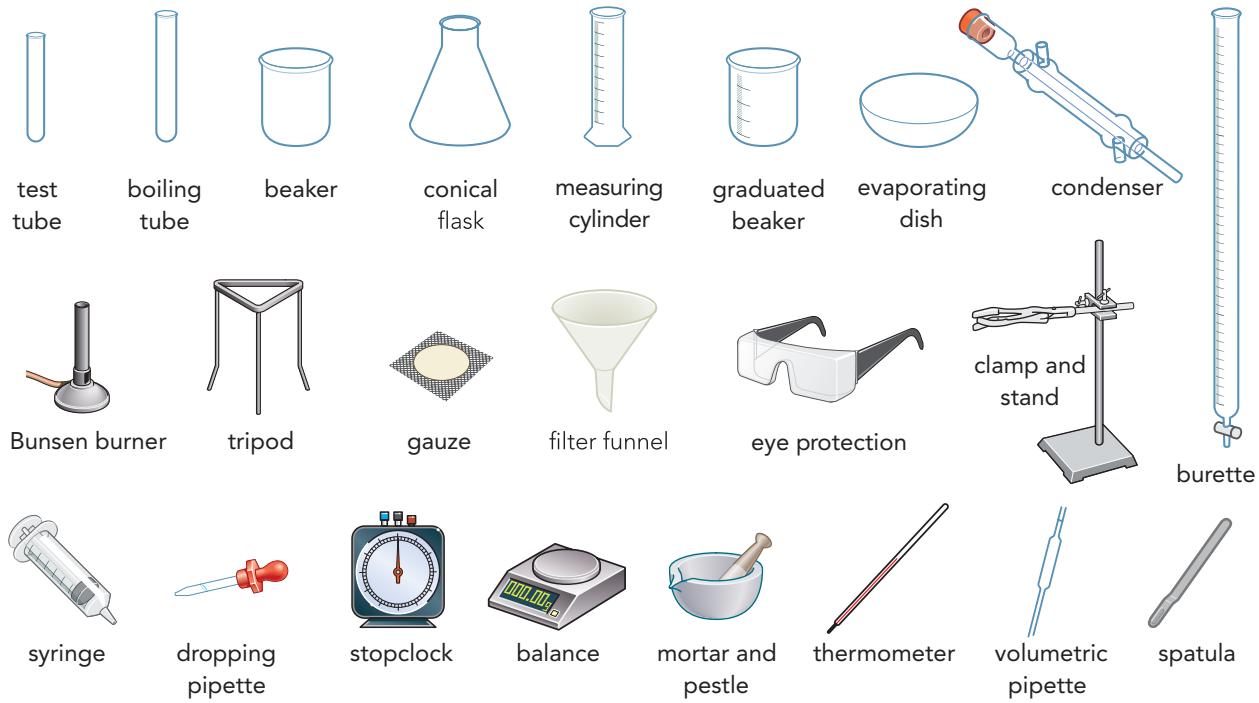

Figure C12.03: Common laboratory equipment.

Equipment for measuring time, mass, temperature, pH and volume

Time is measured using a stopclock or stopwatch. Measurement of time is particularly useful when determining the rate of a chemical reaction (Chapter C6). Digital stopwatches are capable of reading to two decimal places, i.e. to within $\frac{1}{100}$ second (0.01 second).

Mass can be measured approximately in spatula amounts, e.g. add one spatula of a compound to 2 cm^3 of acid, or more accurately by using a top-pan balance.

A simple balance may have a low **resolution**, e.g. 0.1 g, whereas more complex balances may have a higher resolution of 0.001 g or greater. The resolution is the smallest change in a measurement that can be detected.

Temperatures in practical work are measured in degrees Celsius (°C) using a thermometer. Often these are simple liquid thermometers (spirit or mercury), which can be read to the nearest degree. It is also possible to use a digital temperature probe, which can provide a higher level of resolution, e.g. to within 0.1 °C.

pH can be measured using either universal indicator paper or, more accurately, with a digital probe (Figure C12.04). A digital probe may read to 0.1 or even 0.01 on the pH scale, giving significantly higher resolution. However, **calibration** may be required before using a digital meter; this involves using known standards to check values.

Volume can be measured using a beaker, a measuring cylinder, a syringe, a volumetric pipette or a burette. The equipment used depends on the accuracy needed. For example, a beaker could be used to prepare a water-bath containing 100 cm^3 of water, but it could not be used to measure accurately 25.0 cm^3 of alkali for use in an acid–base titration (see later in this chapter). For general use, a measuring cylinder will often provide a sufficient level of accuracy. A volumetric pipette is the most accurate piece of apparatus for measuring a fixed volume of liquid (typically volumetric pipettes are either 10.0 cm^3 or 25.0 cm^3). A burette is the most accurate piece of apparatus for measuring a variable volume (often between 0 and 50.0 cm^3).

KEY WORDS

resolution: the smallest division on the instrument, e.g. this could be 1 mm on a ruler or 0.1 g on a balance.

calibration: the process of checking that the device gives accurate values by using it to read samples with known values.

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Figure C12.04: Digital pH meter being used by a research scientist to test water quality.

Some experiments produce a gas. The volume of gas released during a reaction can give useful information for quantitative purposes as well as when investigating rates of reactions (Chapter C6). Most experiments use one of two standard methods for capturing a gas: direct capture into a gas syringe or by displacement of water in a measuring cylinder (Figure C12.05).

Accuracy and precision of the data recorded

The data obtained from an experiment should be accurate; this means that the value obtained is close to the true value. For example, in a particular acid–base titration, the true volume of acid needed to neutralise 25.0 cm^3 of alkali is 14.10 cm^3. When carrying out the experiment, one student recorded values of 12.45 cm^3, 12.55 cm^3 and 12.5 cm^3. These data are precise. This means the repeated values show only a small difference between them. However, the data are not accurate because the results differ from the true value. Another student recorded values of 14.30 cm^3, 14.00 cm^3 and 14.15 cm^3. These data are not precise as the repeated values show larger differences, but it is more accurate as the mean is closer to the true value. In the diagrams in Figure C12.06, the true value is represented as the centre spot of the circle.

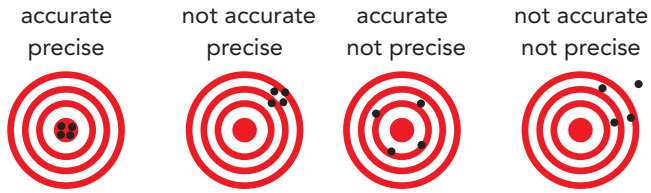

Figure C12.06: Accuracy versus precision.

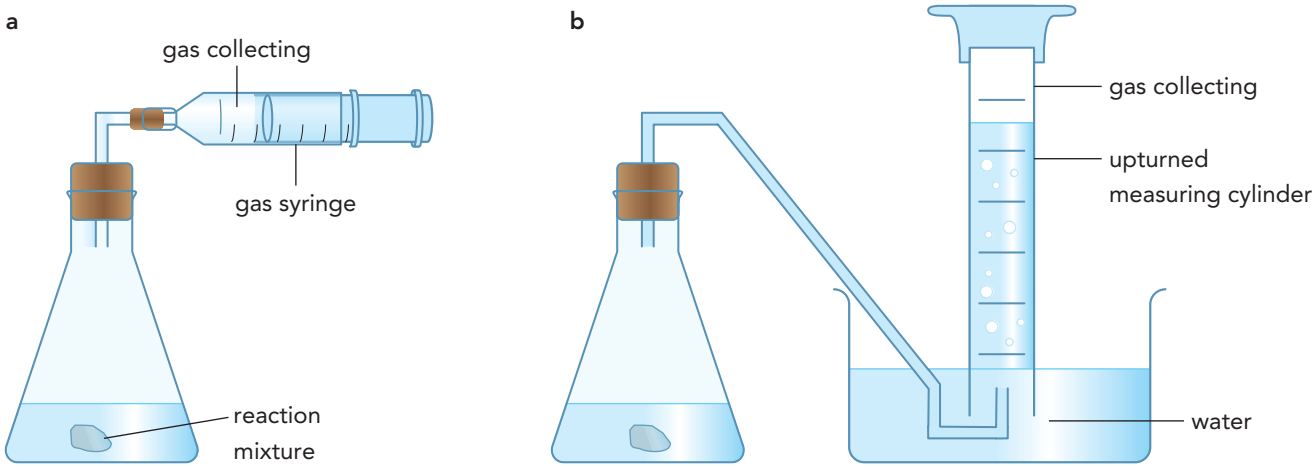

Figure C12.05: Collecting and measuring the volume of a gas: **a:** in a gas syringe and **b:** over water in an inverted measuring cylinder.

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Repeatable and reproducibility

When chemists carry out reactions, they should consider the different factors that influence their results. Reliable data have **repeatability** and are **reproducible**. Data are repeatable when the same person has conducted an experiment several times and obtained similar results. Data can only be reproducible when several different people have performed an experiment with similar variables and obtained similar results.

Variables

To ensure experimental work is both repeatable and reproducible, the variables need to be considered when planning an experiment. There are three main types of variable:

- **controlled variable**
- **independent variable**
- **dependent variable**.

A controlled variable is a variable that is kept constant throughout an experiment. As an example, consider a student who wanted to investigate how the type of metal changed the rate of reaction when added to sulfuric acid. To give repeatable results, as the rate of a reaction is dependent on both concentration and temperature, they would have to use the same starting temperature and concentration of the acid in each experiment. Temperature and concentration are, therefore, controlled variables.

The independent variable is the variable that is changed during an experiment. In the experiment investigating how the type of metal changed the rate of reaction, the type of metal is the independent variable. The independent variable forms the *x*-axis (horizontal axis) of a graph. The dependent variable is the variable that is measured during an experiment, e.g. the rate of the reaction, and this will form the *y*-axis (vertical axis) of a graph.

Sources of error and display of observations

As part of the experimental design, it is useful to consider the sources of error. Almost every measurement has some degree of error or uncertainty in it. Some pieces of apparatus are more accurate than others.

There are two main types of sources of error: **random errors** and **systematic errors**. The impact of random errors can be reduced by repeating an experiment several times, removing any **anomalous** data and taking an average. Systematic errors mean the data are wrong by the same amount each time. An example of this is a **zero error**, i.e. the apparatus is producing a value when it should not. For example, if there is no mass on a top-ban balance the reading should be 0.00 g. Systematic errors can be reduced by 'taring' the apparatus or subtracting the zero error from all results.

An awareness of accuracy and sources of error is important in evaluating the results of an experiment. Tables and graphs of results should be checked for results that do not fit the pattern. A typical graph is shown in Figure C12.07.

When you plot graphs, the line through the points should be a 'best-fit' line. Do not try to include points that are obviously out of place. The line you draw, after carefully plotting the points, should show the general trend or pattern of the results. Very often this will be a straight line or a gentle curve. Try to draw the line so that the points are evenly scattered on either side of the line. If a curve seems to be the best fit, then make the line as smooth as possible.

KEY WORDS

repeatability: where an experiment (or series of experiments) can be repeated using the same method and obtain *reproducible* (similar) results.

reproducible: data when several different people have performed an experiment with similar variables and obtained similar results.

controlled variable: a variable that is kept the same during an investigation.

independent variable: the variable that is altered during a scientific investigation.

dependent variable: the variable that is measured during a scientific investigation.

random errors: these are unpredictable variations in results caused by factors such as human errors.

systematic errors: these are consistent errors that may arise because of a problem with the experimental design or in a piece of equipment being used.

anomalous: something that is unusual or unexpected and deviates from the normal; one of a series of repeated experimental results that is much larger or smaller than the others is an anomalous result.

zero error: a type of systematic error in a measuring instrument, e.g. the reading on a balance may not reset to zero when there is nothing on the balance.

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The key points when drawing graphs are:

- Plot the independent variable ('Temperature' in Figure C12.07) on the *x*-axis (horizontal axis).
- Plot the dependent variable ('Time' in Figure C12.07) on the *y*-axis (vertical axis).
- Make the scales as large as possible: the scales do not have to start at zero.
- Label each axis with the name of the variable and its units.
- Give the graph a title.
- Plot the points with a cross (or a dot in a small circle) using a sharp pencil.
- Draw the best-fit line, which does not have to pass through all the points and which may be a straight line or a curve.

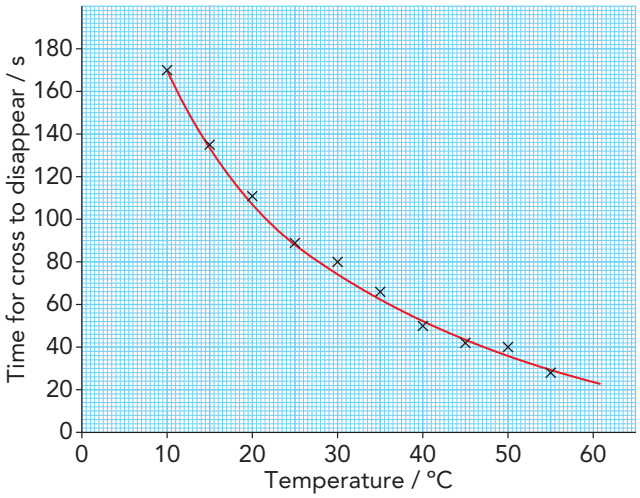

Figure C12.07: Plotting a graph is important to get the most from experimental data. This sample graph is from an experiment such as the one in Chapter C6 (Figure C6.14).

A point that does not fit the pattern is probably due to a random error in a particular reading. A line that should pass through the origin but does not do so could be due to a systematic error.

Safety

Safety is of great importance in experiments. You should be aware of the possible dangers associated with the apparatus and with those chemicals that can pose a risk.

When you plan your investigation, it is important to assess the risks associated with each part of the experiment and to take the relevant safety precautions.

Questions

C12.01 A student wanted to accurately measure the temperature change for the reaction between a solution of sodium carbonate and hydrochloric acid. What equipment would you advise they select to measure the temperature and volumes?

C12.02 The true time for a reaction is 1.06 min. A student measured the time for the experiment and recorded results of 1.23 min, 1.22 min and 1.23 min. The teacher said that these data were accurate but not precise. Was the teacher correct? Explain your answer.

C12.03 A student used a balance with a resolution of 0.1 g to measure 1.3 g of magnesium ribbon. They added this to 10.0 cm^3 of 1.0 mol/dm^3 hydrochloric acid using a 20 cm^3 measuring cylinder with a resolution of 0.5 cm^3. How could any random errors associated with this experiment be reduced?

C12.02 Separation and purification

Standard separation techniques

A mixture can be separated using physical processes. Different types of mixture require different standard techniques, including:

- using a suitable solvent
- **filtration**
- **crystallisation**
- **simple distillation**
- fractional distillation
- **chromatography**.

KEY WORDS

filtration: the separation of a solid from a liquid, using a fine filter paper which does not allow the solid to pass through.

crystallisation: the process of forming crystals from a saturated solution.

simple distillation: a distillation method for separating the liquid solvent from a solution containing dissolved solids.

chromatography: a technique employed for the separation of mixtures of dissolved substances, which was originally used to separate coloured dyes.

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This topic focuses on techniques using a suitable solvent, filtration, crystallisation and distillation. Chromatography will form the basis of Topic C12.03.

The method of separation selected depends on the states of the chemicals involved. To separate a mixture containing a solid and a liquid, e.g. fine mud particles from water, requires filtration. To separate a mixture of two or more liquids with different boiling points requires distillation. To remove water from a solution to give a salt (ionic compound) requires crystallisation. It may be possible to separate two solids using a suitable solvent that will dissolve one solid and not the other. An example of this is the separation of salt and sand. The salt would dissolve into the water giving a solution, whereas the sand is insoluble and could then be removed by filtration.

Separation using different solvents

Differences in solubilities can be used as a simple method for separating mixtures of solids. Compounds with different types of structure will show different solubilities. For example, metallic structures are insoluble in all solvents. Ionic compounds, such as sodium and potassium salts, are often very soluble in water (dissociating into their ions). Simple molecular substances such as the halogens are soluble in hexane and water. Others, particularly organic compounds, dissolve in hexane but not water. Giant covalent compounds, such as diamond and silicon dioxide, are insoluble.

When separating a mixture of two solids, first select a solvent in which one is soluble and the other is insoluble. After adding the solvent, the mixture should be filtered (see next topic). This gives a **residue**, which can be dried (the insoluble material) and a solution of the soluble compound. The soluble compound can be recovered by evaporating the solvent.

For example, to separate a mixture of sulfur and iron filings, toluene is added as the solvent. The mixture is then filtered. The iron filings are insoluble and so are left behind on the filter paper. The sulfur dissolves into the toluene and is then crystallised by evaporation of the solvent.

Filtration

Filtration is used to separate an insoluble solid from a liquid (Figure C12.08a). The liquid part that passes through the filter is called the **filtrate** and the solid part that remains after filtration is called the residue.

The useful product could be either the filtrate or the residue and care is needed to avoid disposing of the wrong part. For very fine solids, filtration can be carried out using a Buchner funnel and vacuum flask (Figure C12.08).

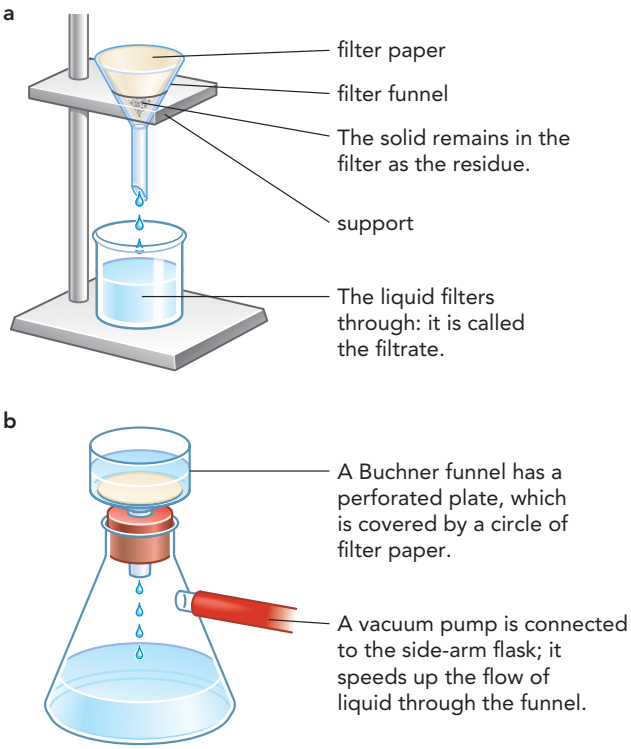

Figure C12.08: Filtration separates an insoluble solid from a liquid using **a:** gravity filtration or **b:** a Buchner funnel.

Crystallisation

Crystallisation is used to remove water from a solution containing an ionic compound (salt). This process works because the water has a lower boiling point than the salt. Evaporation can be carried out by carefully heating the sample in an evaporating basin or by placing the basin over a beaker of boiling water. Using boiling water avoids overheating the sample and prevents material from being lost because of rapid boiling of the liquid. To obtain larger crystals, a little water can be evaporated and then the solution left to cool and evaporate at room temperature.

The crystals can be dried between filter papers.

KEY WORDS

residue: the solid left behind in the filter paper after filtration has taken place.

filtrate: the liquid that passes through the filter paper during filtration.

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EXPERIMENTAL SKILLS C12.01

Filtration and crystallisation of sodium chloride

This experiment uses a simple two-part method for obtaining pure crystals of sodium chloride (salt) from rock salt. You will learn how to use the techniques of filtration and crystallisation.

You will need:

- sample of rock salt
- spatula
- mortar and pestle
- glass rod
- 50 cm^3 measuring cylinder
- 100 cm^3 beaker
- filter funnel and filter paper
- 100 cm^3 conical flask
- evaporating basin
- Bunsen burner
- tripod
- gauze
- heat-resistant mat.

Safety

Wear eye protection throughout. Ensure long hair is tied back when using a Bunsen burner. Care must be taken when evaporating the water to avoid the salt from spitting.

Getting started

You should check the different solubilities of sand and sodium chloride by placing one spatula of each into a beaker containing 10 cm^3 of water. Does the sand dissolve? Does the salt dissolve? What does this tell you about the solubilities of these two substances? Can you link the difference in solubility to the bonding in the substances?

Method

1 Grind two heaped spatulas of rock salt using the mortar and pestle.

2 Carefully transfer the ground up salt to a beaker and add 50 cm^3 of cold water. Stir the mixture with a glass rod.

3 Carefully set up the equipment as shown in Figure C12.09 and filter the mixture into a conical flask. This will remove the insoluble materials and leave a solution of sodium chloride and water (the filtrate).

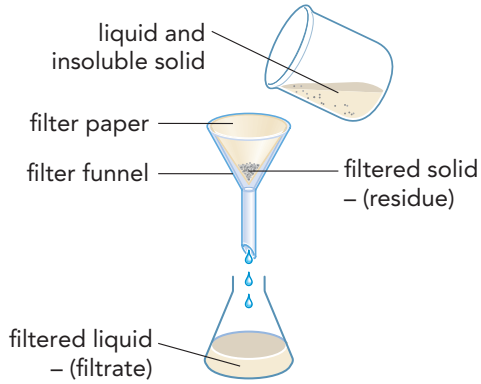

Figure C12.09: Filtration to remove the insoluble components of the rock salt mixture.

4 Place the filtrate into an evaporating basin and heat over a water-bath (Figure C12.10). Allow water to evaporate until crystals of salt start to form when a glass rod is placed in the solution.

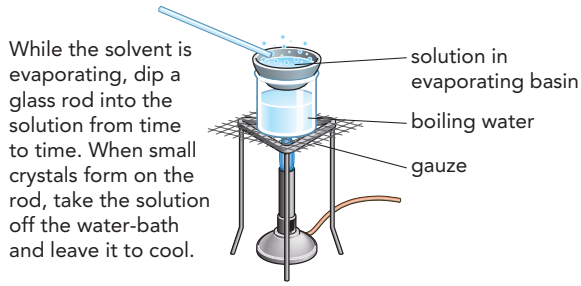

Figure C12.10: Evaporation method to produce the salt crystals.

5 Leave the evaporating basin overnight so that the rest of the water evaporates.

6 Pat dry the crystals between filter papers.

Questions

1 In filtration, the liquid that passes through the filter paper is called the filtrate. What general name is given to the insoluble part?

2 What advantage is there to the rock salt being ground up using a mortar and pestle rather than leaving it in larger pieces?

3 Why is it possible to obtain salt crystals by crystallisation? Would this method work for preparing iodine crystals from an aqueous solution of iodine?

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Distillation

Simple distillation is used to separate the solvent from a solution containing a dissolved solid. The boiling point of the liquid is usually very much lower than that of the dissolved solid. The liquid solvent is more volatile than the dissolved solid and can easily be evaporated off in a distillation flask. **Anti-bumping granules** are often added to the liquid being distilled to prevent the formation of large bubbles in the liquid during boiling (Chapter 1). The solvent vapour is condensed by passing it down a water-cooled condenser and then collected as the **distillate**.

Seawater is a solution of various salts in water and Figure C12.11 shows how pure water can be obtained by simple distillation. Simple distillation can be used to obtain drinking water from salt water on a large scale (desalination).

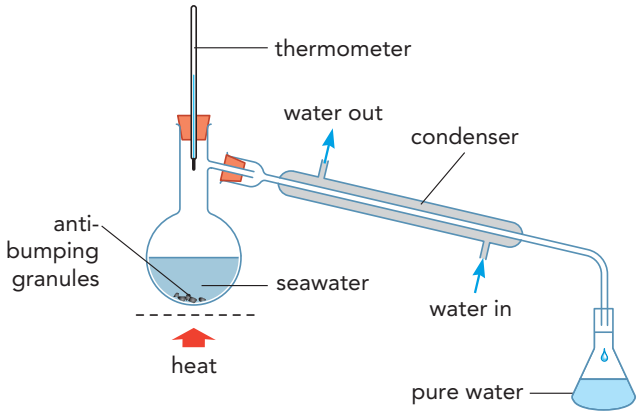

Figure C12.11: Simple distillation of seawater.

Separating the liquids from a mixture of two (or more) miscible liquids is again based on the fact that the liquids will have different boiling points. However, the boiling points are closer together than for a solid-in-liquid solution and fractional distillation must be used (Figure C12.12). In fractional distillation, the most volatile liquid in the mixture distils first and the least volatile liquid distils last.

For example, ethanol boils at 78 °C whereas water boils at 100 °C. When a mixture of the two is heated, ethanol and water vapours enter the fractionating column. Glass beads in the column provide a large surface area for condensation (Figure C12.12). Evaporation and condensation take place many times as the vapours rise up the column. There is a range of temperatures in the column; higher at the bottom and lower at the top. Ethanol passes through the condenser first as the temperature of the column is raised above its boiling point. Water condenses in the column and flows back into the flask because the temperature of the column is below its boiling point of 100 °C.

KEY WORDS

anti-bumping granules: small granules that help reduce the size of bubbles formed when a liquid boils; used for safety to stop the flask shaking.

distillate: the liquid collected in the receiving flask during distillation.

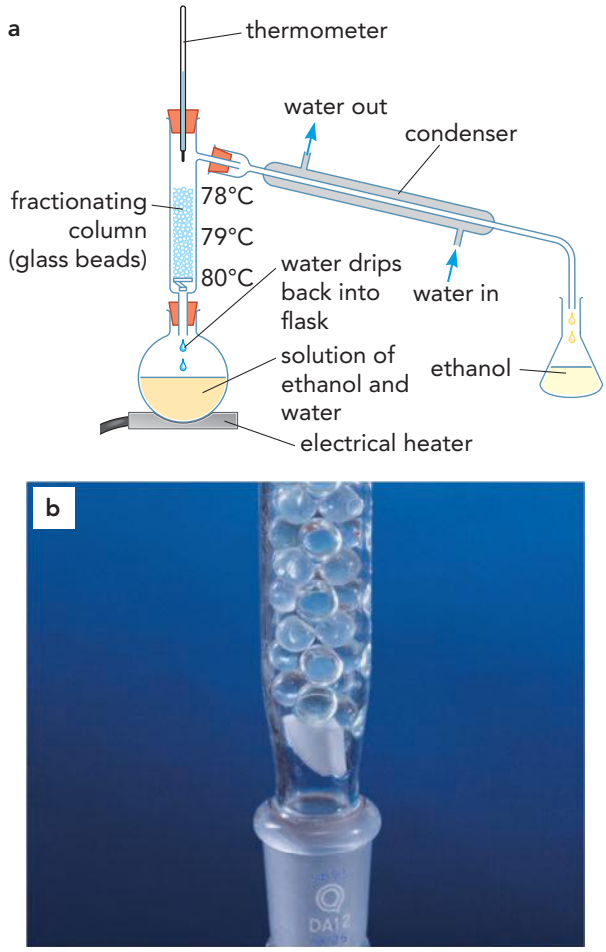

Figure C12.12 a: Separating a mixture of ethanol (alcohol) and water by fractional distillation. **b:** A close-up of the glass beads in the fractionating column.

The temperature on the thermometer stays at 78 °C until all the ethanol has distilled over. Only then does the temperature on the thermometer rise to 100 °C and the water distils over. By watching the temperature carefully, the two liquids (fractions) can be collected separately. Fractional distillation is a very important industrial process and is used in the separation of petroleum fractions (Chapter C11).

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EXPERIMENTAL SKILLS C12.02

Distillation: pure water from inky water

In this experiment, a mixture of ink and water will be separated to give pure water. The experiment uses simple distillation and is based on the different boiling points of the water and ink (water has a lower boiling point than ink).

You will need:

- inky water (mixture of ink and water)
- round-bottomed flask
- thermometer
- Liebig condenser
- Bunsen burner or electric heater (heating mantle)
- anti-bumping granules
- conical flask.

Safety

Wear eye protection throughout. Ensure long hair is tied back when using a Bunsen burner.

Getting started

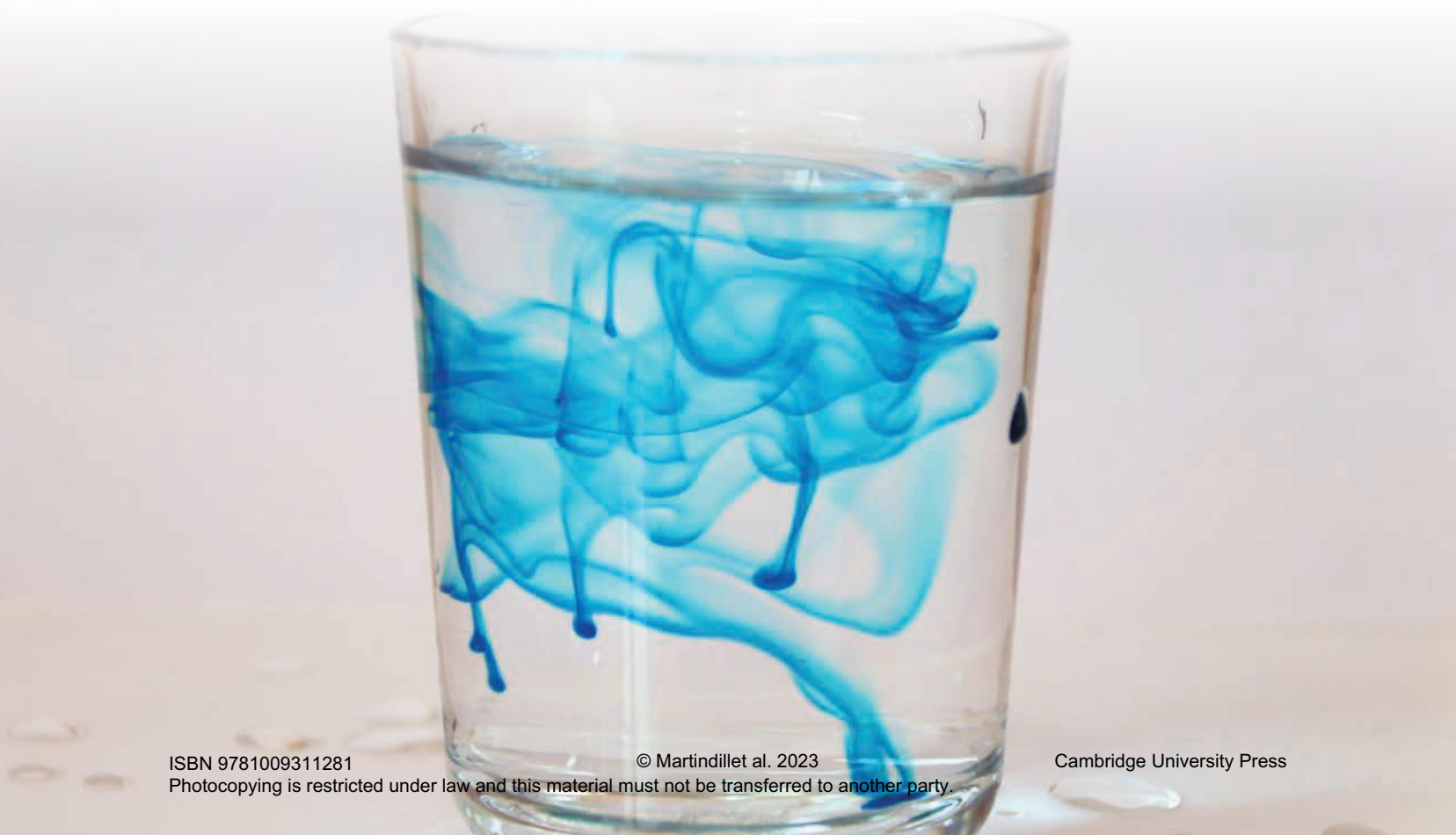
Distillation is used to produce petrol from petroleum and in the purification of ethanol (Chapter C11). What two processes take place during distillation?

Method

1. Set the equipment up as shown in Figure C12.11.
2. Place the inky water into the round-bottomed flask and add a few anti-bumping granules (these are unevenly shaped pieces of an insoluble material added to a liquid to make it boil more calmly).
3. Gently heat the inky water.
4. Record the temperature at which the liquid starts to boil, using the thermometer.
5. Collect the distillate in a conical flask. Record its appearance in comparison to the inky water.

Questions

1. What property of the components in a mixture of liquids is used to bring about separation?
2. What temperature does steam condense at?
3. The technique used in this experiment is simple distillation. Explain how distillation is used to separate a mixture of liquids.



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Component 1	Component 2	Technique	Example
solid	solid	use of suitable solvent: separates on basis of different solubilities	sand (giant covalent) and sodium chloride (ionic)
insoluble solid	liquid	filtration: separates the solid (residue) and the liquid (filtrate)	copper(II) oxide (residue) and water (filtrate)
soluble solid	liquid	crystallisation: the liquid is evaporated to leave the solid	copper(II) sulfate from water
liquid	liquid (miscible)	distillation/fractional distillation: separates on basis of different boiling points	a mixture of different hydrocarbons, e.g. crude oil

Table C12.01: Overview of separation techniques.

Selecting the correct separation technique

We have looked at a range of simple separation techniques. When selecting which technique to use, the most important consideration is the nature of the mixture to be separated. Table C12.01 provides an overview of which technique to use for a range of two-component mixtures.

Testing purity by melting point analysis

The physical separation techniques we have looked at provide methods to produce pure substances from a mixture. A simple test for purity is to measure a melting point or boiling point and compare this to a standard reference value. For example, pure water (ice) melts at 0 °C, pure copper melts at 1085 °C, pure aspirin (acetylsalicylic acid) melts at 135 °C and pure oxygen melts at −218.8 °C. As with other physical properties, melting and boiling points can be used to identify a substance.

When a substance is impure, the melting point will change. Whereas a pure substance melts at a defined, specific temperature, a sample containing impurities (i.e. a mixture) will melt at a lower temperature (Chapter C1). Seawater is impure water and it freezes at a temperature well below 0 °C. In addition, the impurity reduces the sharpness of the melting point. An impure substance melts over a range of temperatures, not at a particular temperature.

Measuring the melting point of a sample, therefore, provides a simple check for sample purity. Melting points are measured accurately using digital meters or an electrically heated melting-point apparatus. In the melting-point apparatus, a capillary tube is filled with a small amount of the solid and is placed in a heating block (Figure C12.13). The melting is viewed through a magnifying lens (Figure C12.14). Alternatively, the sample in the capillary tube can be attached to a thermometer and melting achieved using a water or oil bath.

Figure C12.13: An electrically heated melting-point apparatus.

The presence of impurities will also alter the temperature at which a substance boils. As with melting points, pure substances have fixed, well-defined boiling points (e.g. pure water boils at 100 °C). The presence of an impurity will lead to the boiling point being raised above this value.

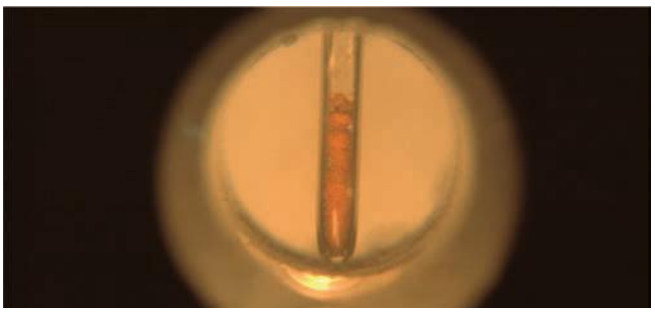

Figure C12.14: Magnified view through a lens of a sample being analysed for its melting point in a melting point apparatus.

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ACTIVITY C12.01

A game of separation

Use a simple game to test other students' understanding of separation techniques. The options include:

1 Missing labels: On a piece of card produce a neat diagram of the apparatus used for a particular type of separation technique. On a separate piece of card produce a set of labels to go with the diagram you have just drawn and cut the labels out from the card. Test another student on their ability to place the labels in the correct places. To extend this game design, use more than one set of equipment and have the labels jumbled up. If you want to add an extra level of challenge to the game, then remove labels from your selection and replace them with blank ones. If a blank is picked up, the player needs to correctly complete it.

2 Chemical pairs: Produce a set of 16 playing cards that match up a word or technique to its description (they could include diagrams, e.g. on one card a diagram of a condenser and on its pair the word condenser). Shuffle the cards and lay out face down in a 4 × 4 grid. Take it in turns to turn cards over in order to identify pairs correctly.

3 A game of your choice: You can design a completely different game to help you to learn the different types of separation and purification techniques.

Peer assessment

In pairs, first discuss the game design. Think about how easy it was to start playing the game. How clear were the rules, was there any confusion? How engaging was the game? For example, would people want to play it more than once?

Second, think about the chemistry that was being learnt by playing the game. Were the questions too easy/too hard? How could the design be improved to make it more challenging? Are there other topics that you have learnt about that could also be taught/revised using the game format you used?

Finally, you could be the first to write a short product review for when this game becomes a commercial success.

C12.03 Chromatography

Separating two or more dissolved solids in solution can be carried out by chromatography. There are several types of chromatography, but they all follow the same basic principles. **Paper chromatography** was originally developed as a method for separating soluble pigments (coloured substances such as dyes and inks) using filter paper.

KEY WORDS

paper chromatography: a simple type of chromatography used to separate the components of soluble substances based on their rate of migration in a solvent (mobile phase) on sheets of filter paper (stationary phase).

The coloured substances separate if:

- the pigments have different solubilities in the solvent
- the pigments have different degrees of attraction to the filter paper.

These two factors determine how fast the pigments move across the filter paper.

A drop of concentrated solution is usually placed on a pencil line (the baseline or origin) near the bottom edge of a strip of chromatography paper. A pencil is used to draw the line as it does not dissolve and interfere with the separation. The paper is then dipped in the solvent. The level of the solvent must start below the sample. Figure C12.15 shows stages of separation using paper chromatography.

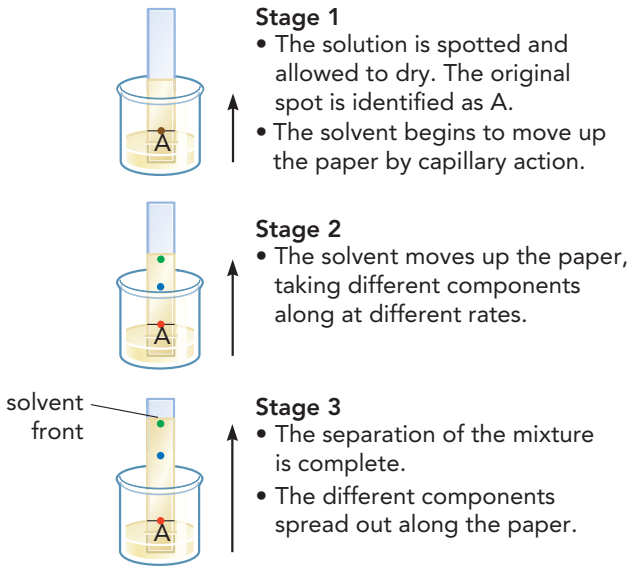

Figure C12.15: Stages of separation in paper chromatography.

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The substances separate according to their solubility in the solvent. As the solvent moves up the paper, the substances are carried with it and begin to separate. The substance that is most soluble moves fastest up the paper. An insoluble substance would remain at the baseline.

The chromatography run is stopped just before the **solvent front** reaches the top of the paper. Figure C12.16 shows the separation of some inks in which you can see the solvent front rising up the paper. The final product of a chromatography experiment can be dried and is known as a **chromatogram**.

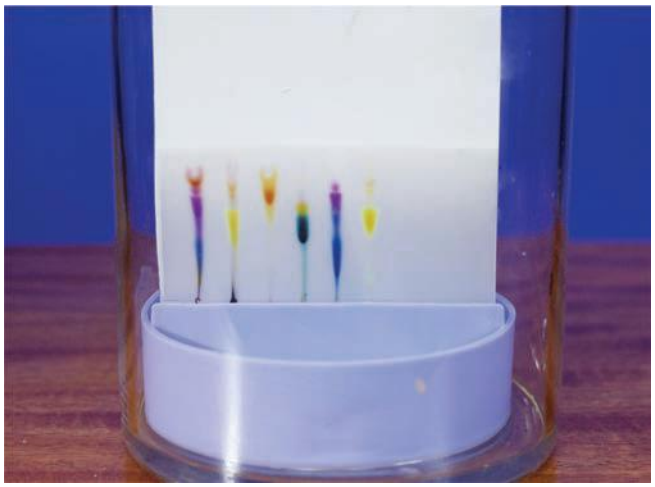

Figure C12.16: Separation of mixtures of inks by paper chromatography.

Many different solvents are used in chromatography. Water and organic solvents (carbon-containing solvents) such as ethanol, ethanoic acid solution and propanone are commonly used. Organic solvents are useful because they dissolve many substances that are insoluble in water. When an organic solvent is used, the process is carried out in a tank with a lid to stop the solvent evaporating.

Using chromatography, we can get more information about the substances present in a mixture. Figure C12.17 shows a chromatogram of a mixture of dyes (labelled X). The three dyes present in the mixture can be seen as the spots vertically above where the sample was spotted on the baseline.

By running pure samples of known dyes A, B and C (sometimes known as reference standards), we can determine whether any of these dyes were present in the mixture X.

By looking horizontally across the chromatogram, we can see that mixture X contains dyes A and C, but not dye B. The chromatogram also shows there is a dye in X that has not been identified in this experiment.

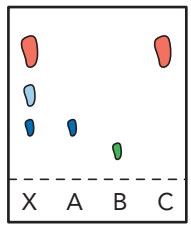

Figure C12.17: A chromatogram of a mixture of dyes X.

Paper chromatography can be used to check for the purity of a substance (Figure C12.19). If the sample is pure, it should only give one spot when run in several different solvents. The identity of the sample can also be checked by comparing its movement to that of a sample we know to be pure.

The distance moved by a particular spot can be measured and related to the position of the solvent front. The ratio of these distances is called the **R_f value** (Figure C12.18).

$$R_f = \frac{\text{distance moved by the substance}}{\text{distance moved by the solvent front}}$$

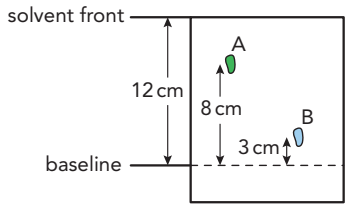

Figure C12.18: Measuring R_f values for substances A and B on a chromatogram.

The R_f value is always the same for a particular substance in a specific solvent at a given temperature. This means it can be used to identify unknown substances by comparison with reference values. From the chromatogram in Figure C12.18 it can be seen that the R_f values for substances A and B are 0.67 and 0.25, respectively. As an R_f value is a ratio, it always ranges between 0 and 1 and does not have any units.

KEY WORDS

solvent front: the moving boundary of the liquid solvent that moves up the paper during chromatography.

chromatogram: the result of a paper chromatography run, showing where the spots of the samples have moved to.

R_f value: in chromatography, the ratio of the distance travelled by the solute to the distance travelled by the solvent front.

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Questions

C12.04 A simple chromatogram from a red marker pen showed two dots in a vertical line. What does this tell you about the ink used in this pen?

C12.05 A student tried to separate some inks from a black marker pen using paper chromatography but the ink remained on the baseline. Why did the ink not move and what should the student do to improve the experiment?

C12.06 When analysing a chromatogram, the distance moved by the solvent from the baseline was 2.8 cm and the distance travelled by the sample was 2.3 cm.

Calculate the R_f value for this compound to 2 decimal places. Using the same ink, but a larger piece of chromatography paper, the solvent front had travelled 9.7 cm. Predict, to 1 decimal place, the distance moved by the sample.

Figure C12.19: Paper chromatography is one of several different types of chromatography that work on the same principle.

EXPERIMENTAL SKILLS C12.03

Paper chromatography

This experiment provides a simple method for analysing the colours in different food dyes or inks. You will learn how to produce a paper chromatogram.

You will also calculate R_f values.

You will need:

- three different inks or liquid food dyes labelled A, B and C
- 250 cm^3 beaker
- water or ethanol as the solvent
- rectangular piece of chromatography paper (approximately 8 cm × 4 cm)
- capillary tube or dropping pipette
- pencil
- ruler
- splint or pencil and bulldog clip to suspend the paper in the solvent
- hairdryer.

Safety

Wear eye protection throughout. Ethanol is toxic and so you must wash your hands after use. Ethanol is also highly flammable and so this experiment must not be conducted near lit Bunsen burners.

Getting started

Selecting the correct solvent for a chromatography experiment is important. If the samples are too soluble, they will travel with the solvent front and not separate; if the samples are insoluble, they will remain on the baseline. Test the solubility of an ink by placing a small amount onto a piece of paper and then submerge the paper in a small amount of solvent. Does the ink remain on the paper or does it start to dissolve into the solvent? Does the ink dissolve more rapidly in different solvents?

Method

1. Draw a pencil line (baseline) horizontally on your piece of chromatography paper and add three crosses (X) at regular intervals. Under each cross write a letter A, B or C.
2. Add a drop of dye A carefully in the centre of the first cross, this should be done with the capillary tube. If using a pipette just touch the end onto the paper, do not squeeze. To get the best results use small amounts of sample, as larger amounts will give very streaky results.

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CONTINUED

3 Repeat with the other dyes, adding them to the crosses labelled B and C.

4 Attach the paper to a splint or pencil using a clip and suspend the paper in the solvent (water). It is essential that the height of the solvent is between the bottom of the paper and the baseline.

5 The solvent should start to travel up the chromatography paper and any soluble dyes will start to move from the baseline.

6 Remove the paper from the water after the solvent has travelled about 80% of the way up the paper.

7 Mark the solvent front with a pencil to show how far the solvent moved.

8 Dry the chromatogram carefully with the hairdryer.

9 Work out the R_f values for the different dyes.

The experiment can be repeated using ethanol as an alternative solvent. If using ethanol, a lid should be added to the equipment.

Questions

1 A student repeated the experiment using inks from a selection of permanent pens and the following method:

- **a** Draw a baseline in pen horizontally on your piece of chromatography paper. The baseline should be about 0.5 cm from the bottom of the paper.
- **b** Add a drop of ink at regular intervals along the baseline.
- **c** Attach the paper to a pencil using a bulldog clip and suspend the paper in water so that the baseline is just covered by the water.
- **d** Remove from the water once the solvent has travelled all the way up the paper.
- **e** Mark the solvent front in pencil.

Can you spot the errors in their method?

Explain the impact of each mistake they have made.

2 Why would a lid be required if ethanol was used as a solvent?

ACTIVITY C12.02

Mixing it up

1 Write down five facts linked to the different separation techniques, e.g. the liquid that passes through the filter paper is called the filtrate (Figure C12.20).

2 Write down two detailed explanations of how two of the different separation techniques work, e.g. fractional distillation involves heating a mixture to its boiling point, different fractions have different boiling points and so evaporate at different temperatures, etc.

3 Identify one question you still have about separation techniques or one technique you are not yet confident with.

In pairs, compare your facts and then work together to identify which three facts you think are the most important.

Figure C12.20: Filtering flower essence at a perfume factory in France.

Peer assessment

Look at your partner's explanations of two different separation techniques. What are the strengths in your partner's explanations? How could their explanation be improved?

Finally, find an answer or explanation for your partner's question or try to explain to them the technique they are not yet confident with.

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REFLECTION

One of the key skills in chemistry is the ability to design an experiment. In this chapter, we have considered not only the way in which apparatus is selected but also the techniques used to purify the products of chemical reactions. How will you apply your understanding of experimental design to suggest improvements in future practical experiments? Thinking back to the flow diagram given in Figure C12.02, what aspects of your experimental work do you still need to develop? How could you do this?

C12.04 Identification of ions and gases

Tests to identify common cations

We all require certain levels of metal ions (cations) such as sodium, potassium, copper, iron and zinc to maintain a healthy body. However, in larger concentrations, some metal ions can become dangerous to human health, e.g. high levels of lead ions are linked to Alzheimer's Disease.

It is important for analytical chemists to detect the presence of metal ions in solution. In the following topics we will look at two **qualitative** approaches to identifying a range of cations. These are the flame tests and precipitation reactions with aqueous sodium hydroxide or aqueous ammonia.

Flame tests to identify metal cations

As we have seen in Chapter C2, the distinctive colours produced in a firework display result from the different metal compounds that are used in the manufacture of the fireworks with different metals giving rise to different colours. This same principle is used as the basis for the flame test to test for the presence of some metal cations. In particular, the flame test is widely used for metal ions of the elements found in Group I (alkali metals) and Group II (Figure C12.21).

KEY WORD

qualitative: the process used to determine the presence or absence of a substance in a given sample.

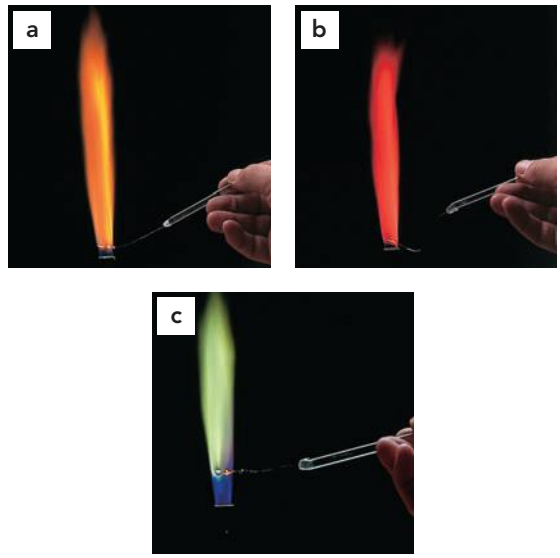

Figure C12.21: Some Group II metals give characteristic colours in the flame test: **a:** calcium, **b:** strontium and **c:** barium.

The test for the presence of metal cations involves taking a nichrome wire probe and first heating it in a roaring Bunsen flame. The wire is then dipped into hydrochloric acid. These two steps are repeated several times until no residual colour is evident in the flame. This is done to clean the probe by removing traces of metal ions from previous experiments. The probe is then dipped into the acid again to wet it before placing the probe into the test sample. The wet probe will pick up a few crystals. The probe is then placed into a roaring flame and the colour is recorded. These steps are outlined in Figure C12.22.

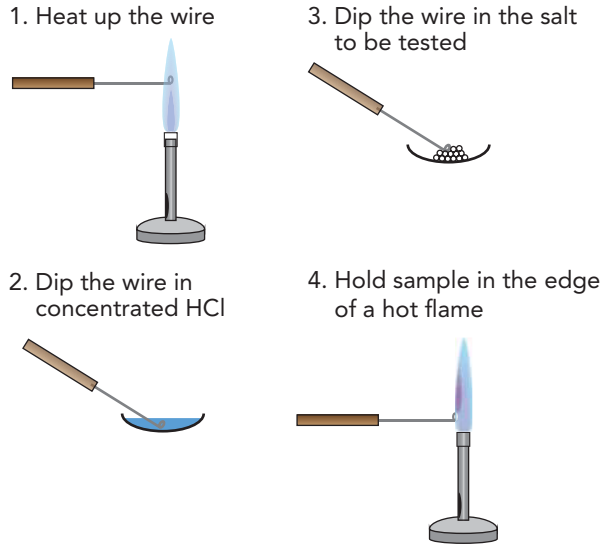

Figure C12.22: Method for the flame test.

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Different metal ions produce characteristic colours (Table C12.02).

	Lithium, Li^+	Sodium, Na^+	Potassium, K^+	Copper(II), Cu^{2+}
flame colour	red	yellow	lilac	blue–green

Table C12.02: Standard colours obtained with the flame test for different metal ions.

An alternative method is to take a wooden splint and dip it in a solution of the metal ion for an extended period of time. The wooden splint will absorb the test chemical and can then be placed into a roaring Bunsen burner flame (Figure C12.23). This will give similar results to those recorded in Table C12.02. You must take care not to set the splint on fire. If this does happen the flame will turn yellow and the results will be void as the yellow flame of the burning wood will dominate the colour of the metal ion.

Figure C12.23: Using a splint, or rolled paper, as an alternative method for the flame test: the yellow flame shows the presence of sodium.

Questions

C12.07 Explain how a nichrome wire probe and Bunsen burner can be used to show the presence of sodium ions.

C12.08 Flame tests on three different metal sulfates (SO_4^{2-}) gave three different coloured flames: lilac, red and blue–green. What metal ion was present in each test? Deduce the formulae of the three sulfates that were tested.

Precipitation with aqueous sodium hydroxide

Not all aqueous ions produce characteristic flame colours and so alternative tests are needed. A commonly used test is to add aqueous sodium hydroxide NaOH(aq). When sodium hydroxide solution is added to a solution containing a metal cation (usually a transition metal ion), an insoluble metal hydroxide is formed in a **precipitation reaction**. The transition metals are particularly well suited to this test as they form compounds with characteristic colours.

Precipitation reactions are less useful for salts containing Group I or Group II metal ions. Salts of the Group I metals tend to be soluble while those of Group II, if they do produce a **precipitate**, will produce a white precipitate that requires additional tests to identify the specific metal ion.

KEY WORDS

precipitation reaction: a reaction in which an insoluble salt is prepared from two aqueous solutions.

precipitate: an insoluble salt formed during a precipitation reaction.

An example of this is the addition of dilute sodium hydroxide to aqueous iron(II) ions which will initially produce a green precipitate (Figure C12.24).

iron(II) chloride	+	sodium hydroxide	→	iron(II) hydroxide	+	sodium chloride
$FeCl_2(aq)$	+	$2NaOH(aq)$	→	$Fe(OH)_2(s)$	+	$2NaCl(aq)$

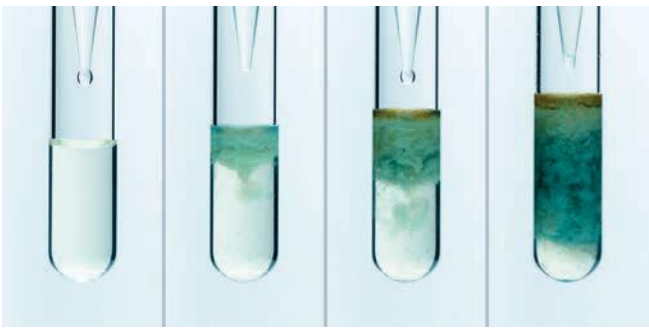

Figure C12.24: Precipitation reaction as sodium hydroxide solution is added to a solution containing aqueous iron(II) ions.

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If left to stand, iron(II) hydroxide will slowly oxidise to iron(III) hydroxide at the surface of the reaction leading to a change in colour (green to brown) (Figure 12.24).

You can use a solution of aqueous sodium hydroxide to test for cations including ammonium, calcium, copper(II), iron(II), iron(III) and zinc. The result of the precipitation reaction for each ion is given in Table C12.03.

Cation	Positive result when NaOH(aq) added
ammonium, NH_4^+	no precipitate but produces ammonia on warming
calcium, Ca^{2+}	white precipitate; this is insoluble in excess NaOH(aq)
copper(II), Cu^{2+}	light blue precipitate; this is insoluble in excess NaOH(aq)
iron(II), Fe^{2+}	green precipitate; this is insoluble in excess NaOH(aq) but starts to turn brown near the surface if left to stand
iron(III), Fe^{3+}	red–brown precipitate; this is insoluble in excess NaOH(aq)
zinc, Zn^{2+}	white precipitate; this will redissolve in excess NaOH(aq) to give a clear, colourless solution

Table C12.03: Results of precipitation reactions using NaOH(aq).

Care needs to be taken when trying to identify zinc and calcium ions as both of these ions produce a white precipitate. This means that a further stage in the analysis is needed. You can identify the calcium ions as they do not redissolve when an excess of sodium hydroxide is added; zinc will redissolve. As an alternative, to show the presence of calcium ions you could also do a flame test (the calcium ions would produce a characteristic orange–red coloured flame).

Questions

C12.09 Dilute sodium hydroxide solution was added dropwise to copper(II) sulfate solution to form a light blue precipitate of copper(II) hydroxide. Which of these symbol equations is/are correct?

A $CuSO_4 + NaOH \rightarrow CuOH + NaSO_4$

B $CuSO_4(aq) + 2NaOH(l) \rightarrow Cu(OH)_2(s) + Na_2SO_4(aq)$

C $CuSO_4(aq) + 2NaOH(aq) \rightarrow Cu(OH)_2(s) + Na_2SO_4(aq)$

D $CuSO_4(aq) + NaOH(aq) \rightarrow Cu(OH)_2(s) + Na_2SO_4(s)$

E $CuSO_4 + 2NaOH \rightarrow Cu(OH)_2 + Na_2SO_4$

C12.10 Which equation from Question C12.09 reveals that the reaction involves precipitation?

Precipitation with aqueous ammonia

A solution of ammonia (NH_3) will also lead to precipitation reactions with solutions containing aqueous metal cations (Table C12.04). The initial changes with dilute ammonia solution are generally similar to those when using aqueous sodium hydroxide. This is because ammonia forms a weakly alkaline solution in water and only produces a low concentration of aqueous hydroxide ions.

Cation	Positive result when NH_3(aq) added
ammonium, NH_4^+	no reaction
calcium, Ca^{2+}	no precipitate or very slight white precipitate
copper(II), Cu^{2+}	light blue precipitate; soluble in excess NH_3(aq) producing a dark blue solution
iron(II), Fe^{2+}	green precipitate; insoluble in excess NH_3(aq) but starts to turn brown near the surface if left to stand
iron(III), Fe^{3+}	red–brown precipitate; insoluble in excess NH_3(aq)
zinc, Zn^{2+}	white precipitate; redissolves in excess NH_3(aq) to give a clear, colourless solution

Table C12.04: Results of precipitation reaction using NH_3(aq).

Ammonia solution produces slightly different results when it is added in excess. For solutions containing zinc ions, a few drops of ammonia solution will produce a white precipitate. When an excess is added, the zinc precipitate dissolves to give a colourless solution. The other difference to note is that copper(II) ions will initially give a characteristic pale blue precipitate but this will redissolve when excess ammonia is added, producing a dark blue solution (Figure C12.25).

Figure C12.25: Precipitation reaction as ammonia solution is added to a solution containing aqueous copper(II) ions.

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EXPERIMENTAL SKILLS C12.04

Testing for aqueous cations

This experiment provides methods for the identification of common metal ions and the ammonium ion (NH_4^+) using sodium and ammonium hydroxide solutions. The method can be used in parallel with the tests for common anions discussed in the next topic to confirm the identity of an ionic compound.

You will need:

- test-tubes
- test-tube rack
- Bunsen burner and heat-resistant mat
- 10 cm^3 measuring cylinder
- dropping pipette
- 0.5 mol/dm^3 sodium hydroxide solution
- 0.5 mol/dm^3 ammonia solution
- damp red litmus paper
- test samples including 0.2 mol/dm^3 solutions of the following compounds: copper(II) sulfate, iron(II) sulfate, iron(III) chloride, ammonium chloride, zinc sulfate and calcium chloride.

Safety

Wear eye protection throughout. Be careful with chemicals. Never ingest them and always wash your hands after handling them. Avoid the chemicals coming into direct contact with skin; if they do then rinse the affected area under running water.

Getting started

Take 2 cm^3 of a solution of iron(II) sulfate and place it in a clean, dry test-tube. Then use the dropping pipette to add a few drops of 0.5 mol/dm^3 sodium hydroxide solution to the tube. Note the formation of a precipitate and in particular its colour.

Leave the test-tube in a rack and look at it again after a further ten minutes. Has there been any change in the colour of the precipitate?

Method

Part 1: Using sodium hydroxide

1. Place 2 cm^3 of a solution of the test sample into a clean test-tube.
2. Slowly add a few drops of dilute 0.5 mol/dm^3 sodium hydroxide solution and record the colour of any precipitate formed.
3. Continue to add dilute sodium hydroxide until it is in excess. This is necessary as some of the precipitates initially formed will redissolve.
4. *Additional step*: to test for the ammonium ion (NH_4^+) repeat steps 1 and 2 but then warm gently using a Bunsen burner. If a gas is produced then it should turn damp red litmus paper blue (see also test for ammonia gas in Topic C12.04).

Part 2: Using ammonia solution

1. Place 2 cm^3 of a solution of the test sample into a clean test-tube.
2. Slowly add a few drops of dilute ammonia solution ($NH_3(aq)$) and record the colour of any precipitate formed.
3. Continue to add dilute ammonia solution until it is in excess. This is necessary as some of the precipitates initially formed will redissolve.

Questions

1. The reaction between transition metal ions and sodium hydroxide produces coloured precipitates. What is a precipitate?
2. Transition metals can form more than one ion. What difference did you note between the precipitates of iron(II), $Fe^{2+}(aq)$ and iron(III), $Fe^{3+}(aq)$?
3. Ammonia turns red litmus blue. What does this tell you about ammonia?

Summary of tests for aqueous cations

The flame test and the simple precipitation reactions using aqueous sodium hydroxide or aqueous ammonia provide qualitative methods of analysis for identifying aqueous cations.

When carrying out these tests it is important that the aqueous solutions are prepared using distilled water. This is because tap water can contain dissolved minerals (metal compounds). These minerals may include metal ions such as calcium and zinc that would potentially interfere with the tests (Chapter C10).

Questions

C12.11 5 cm^3 of iron(II) and iron(III) chloride were placed into separate clean test-tubes and a few drops of aqueous sodium hydroxide solution were added to each tube. Describe the observations for the positive test results expected for each salt.

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C12.12 5 cm^3 of copper(II) sulfate solution was placed into a clean test-tube and aqueous sodium hydroxide was added dropwise. In another experiment, 5 cm^3 of copper(II) sulfate solution was placed into a clean test-tube and dilute ammonia solution was added dropwise. Describe fully what would be seen during each experiment.

Tests to identify common anions

The previous topics have considered the main tests for the presence of common cations (positive ions), but as ionic compounds contain both a positive and a negative ion (anion), analytical techniques are needed for both anions and cations. The common anions include single elements (monatomic ions), e.g. chloride (Cl^-), bromide (Br^-) and iodide (I^-), and compound ions, which, as the name suggests, contain more than one element, one of which is oxygen, e.g. carbonate (CO_3^{2-}), nitrate (NO_3^-) and sulfate (SO_4^{2-}).

Carbonate ions

The test for carbonate ions (CO_3^{2-}) relies on the fact that carbonates react with dilute acids to release carbon dioxide. As this reaction takes place in solution, the gas formed is visible as effervescence. Proof that the gas formed is carbon dioxide is determined by bubbling the gas through limewater. If carbon dioxide is present, the limewater changes from clear to cloudy/milky (Figure C12.26).

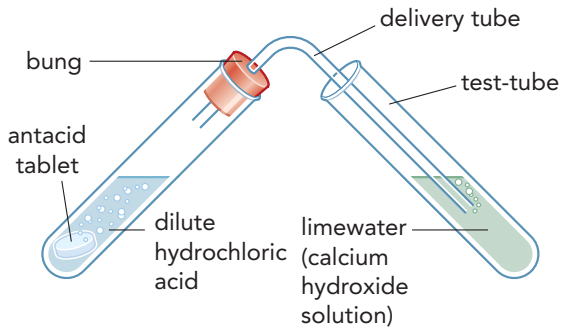

Figure C12.26: Testing for carbonate ions.

Halide ions

The test for halide ions, chloride (Cl^-), bromide (Br^-) and iodide (I^-) is the formation of a precipitate when a solution of acidified silver nitrate is added. The test produces different colours of precipitate: a chloride forms a white precipitate, bromide forms a cream precipitate, and iodide a yellow precipitate (Figure C12.27). The presence of carbonate ions in the test sample can interfere with this reaction and so they need to be removed. This is done by the addition of an acid, which reacts with carbonates to produce carbon dioxide, water and salt. The silver nitrate solution is acidified by adding a small amount of nitric acid.

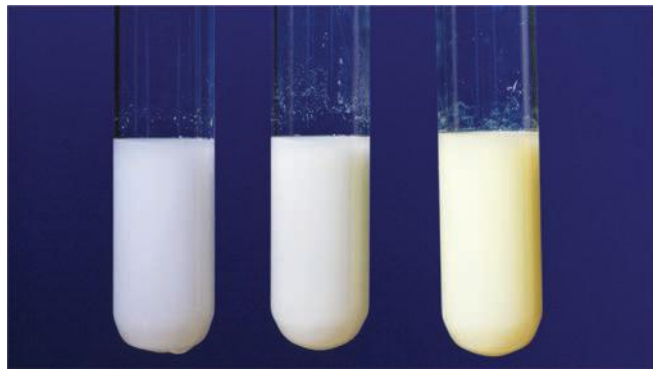

Figure C12.27: Precipitates produced in the tests for halide ions using acidified silver nitrate. The precipitates are silver chloride (white), silver bromide (cream) and silver iodide (yellow).

A solution containing sodium chloride reacts with silver nitrate solution to produce a white precipitate of silver chloride.

sodium chloride + silver nitrate → sodium nitrate + silver chloride

$$NaCl(aq) + AgNO_3(aq) \rightarrow NaNO_3(aq) + AgCl(s)$$

Sulfate ions

The test for sulfate ions (SO_4^{2-}) involves acidification with dilute nitric acid and then addition of aqueous barium nitrate solution. In the presence of sulfate ions, barium nitrate solution reacts to produce a white precipitate of barium sulfate. As with the test for halide ions, the presence of carbonate ions can interfere with the results as insoluble barium sulfate will form. Therefore, the solution is acidified using a small volume of nitric acid (or hydrochloric acid).

A solution containing sodium sulfate reacts with barium nitrate solution to produce a white precipitate of barium sulfate and a solution of sodium nitrate.

barium nitrate + sodium sulfate → barium sulfate + sodium nitrate

$$Ba(NO_3)_2(aq) + Na_2SO_4(aq) \rightarrow BaSO_4(s) + 2NaNO_3(aq)$$

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Nitrate ions

The standard test for nitrate ions (NO_3^-) involves adding aqueous sodium hydroxide, aluminium foil and then heating gently. The nitrate ions are reduced to produce ammonia (NH_3) and the aluminium metal is oxidised to give Al^{3+}. The ammonia produced is a gas and can be tested by placing damp red litmus paper above the neck of the reaction vessel. The positive result for ammonia, and therefore for the presence of nitrate ions, is a colour change of the damp red litmus from red to blue.

Summary of tests for anions

The tests for the anions are unique to individual ions, except for the Group VII halide ions. The presence of carbonate ions can lead to false results if not removed because most carbonates are insoluble. This means we need to acidify reagents to remove carbonate, and care must be taken to ensure the correct acid/reagent pair is selected. For example, using sulfuric acid to acidify barium nitrate solution would introduce sulfate ions. This would lead to the immediate precipitation of barium sulfate before adding it to any test sample.

Table C12.05 summarises the tests for anions.

Anion	Test	Test result
carbonate (CO_3^{2-})	add dilute hydrochloric acid; test for carbon dioxide gas	effervescence (fizzing), carbon dioxide produced (test with limewater)
chloride (Cl^-) (in solution)	acidify with dilute nitric acid, then add aqueous silver nitrate	white precipitate of silver chloride formed
bromide (Br^-) (in solution)	acidify with dilute nitric acid, then add aqueous silver nitrate	cream precipitate of silver bromide formed
iodide (I^-) (in solution)	acidify with dilute nitric acid, then add aqueous silver nitrate	yellow precipitate of silver iodide formed
sulfate (SO_4^{2-}) (in solution)	acidify with dilute nitric acid (or hydrochloric acid), then add barium nitrate solution	white precipitate of barium sulfate formed
nitrate (NO_3^-) (in solution)	add aqueous sodium hydroxide, then add aluminium foil and warm carefully; test for ammonia gas	ammonia gas given off (test with moist red litmus)

Table C12.05: Tests for anions.

Questions

C12.13 The test for carbonate ions can use any dilute acid. Hydrochloric acid is most commonly used but dilute sulfuric acid or nitric acid would also work. Explain why the type of acid used does not matter. Your answer should refer to the equations for each acid when added to sodium carbonate solution.

C12.14 Two solutions were prepared, one of magnesium bromide ($MgBr_2$) and the other of magnesium chloride ($MgCl_2$). How could acidified silver nitrate ($AgNO_3$) be used to show which solution contained the magnesium bromide? Give equations for the two reactions.

C12.15 A student testing for sulfate ions used barium nitrate acidified with dilute sulfuric acid instead of the recommended hydrochloric acid. Would this change in acid have any impact on the student's results? Explain your answer fully.

C12.16 In the test for nitrate ions (NO_3^-), the nitrate ion is reduced to ammonia (NH_3) and the aluminium is oxidised. Write a half-equation for the oxidation of aluminium metal to aluminium ions.

ACTIVITY C12.03

Memorising the standard tests for ions

Work with a partner to produce a set of flash cards for the standard tests for ions. One person could focus on the aqueous anions and the other person could focus on the aqueous cations.

On the front side of each flash card, write the formula and name of the ion being tested. The cations should include Li^+, Na^+, K^+, Ca^{2+}, Cu^{2+}, Fe^{2+}, Fe^{3+}, Zn^{2+} and NH_4^+. The anions should include Cl^-, Br^-, I^-, SO_4^{2-}, NO_3^- and CO_3^{2-}. To help, you might use two different colours for the cards, one for cations and another for anions.

On the reverse of each flash card give the test/reagent and result, e.g. for Li^+ the reverse would say 'Test/reagent = flame test', 'Result = red'. Some ions may require two tests.

Once you have produced a set of flash cards covering both the anions and cations, follow the instructions that follow:

1. Each person selects five cards at random from the set of flash cards and spends one minute learning what is on them.
2. After one minute, pass your cards to your partner.

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CONTINUED

3 Take it in turns to test each other by stating the standard test and result and asking for the ion. For example, 'Which ion could be tested for by using the flame test and gives a blue–green flame?' If your partner gives the correct answer (Cu^{2+}), give their card back, if not you can keep it.

4 Keep taking alternate turns to test each other until all five cards have been used.

5 At the end of the round, count up the number of cards each of you has. The player with the most cards wins that round.

You can use your set of flash cards to play further rounds of the game. For example:

- Swap the original set of five cards between you and your partner.
- Shuffle all of the cards and then deal each player five new cards.
- Test by stating the ion and asking for the standard test.
- Test by stating the ion and asking for the standard test and its result.

Self assessment

How many cards did you win? What tests do you know really well? Which tests do you think you could learn more about? What other information could you have included on the cards to help you remember the tests? Did you think about using online software for creating virtual flash cards?

Tests to identify common gases

Animals and birds have been used to detect the presence of low levels of chemicals in a wide range of situations. Detection ('sniffer') dogs are trained to use their sense of smell to search for illegal drugs, and canaries have been used in coal mines to detect the build-up of carbon monoxide and other toxic gases before they affect humans. Analytical chemists still use very simple tests to detect common gases such as hydrogen, oxygen, carbon dioxide, chlorine and ammonia. These are detailed in the following text and summarised in Table C12.06.

Hydrogen

Hydrogen (H_2) is a colourless and odourless gas.
The standard test for hydrogen is to place a lighted splint at the neck of a test-tube. If hydrogen is present, there will be a characteristic 'squeaky pop' sound due to a small explosion as the hydrogen and oxygen rapidly react to produce water. The test is often referred to as 'the squeaky pop test'.

Gas	Test	Positive result
hydrogen (H_2)	lit splint	produces a squeaky pop
oxygen (O_2)	glowing splint	the splint is relit
carbon dioxide (CO_2)	bubble through limewater	turns from clear to cloudy/milky
chlorine (Cl_2)	damp litmus paper	bleached white
ammonia (NH_3)	damp red litmus paper	turns from red to blue

Table C12.06: Summary of tests for gases.

Oxygen

Oxygen (O_2) is a colourless, odourless gas. The standard test for oxygen is to place a glowing splint into a test-tube of the gas. If oxygen is present, the splint will relight (Figure C12.28). This is because substances burn much more rapidly in pure oxygen.

Figure C12.28: A glowing splint being relit by oxygen in a test-tube.

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Carbon dioxide

Carbon dioxide (CO_2) is a colourless, odourless gas. To test for carbon dioxide the gas is bubbled through limewater (a dilute aqueous solution of calcium hydroxide) (Figure C12.29). If carbon dioxide is present, the limewater turns from clear and colourless to cloudy/milky due to the formation of insoluble calcium carbonate.

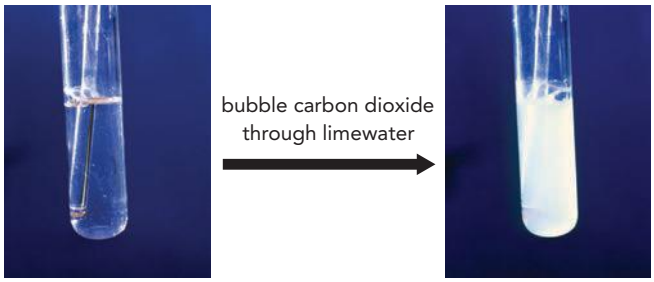

Figure C12.29: The limewater test for carbon dioxide.

Chlorine

Chlorine (Cl_2) is a toxic, green gas with a distinctive odour. The standard test for chlorine is to use damp blue litmus paper. The damp blue litmus paper will initially turn red before being bleached white (Figure C12.30). The chlorine gas reacts with the water to form hydrochloric acid (HCl) and hydrogen chlorate(I) (hypochlorous acid, HClO). The presence of hydrochloric acidic results in the blue litmus paper turning red. The hypochlorous acid is a bleaching agent and causes the litmus paper to turn white.

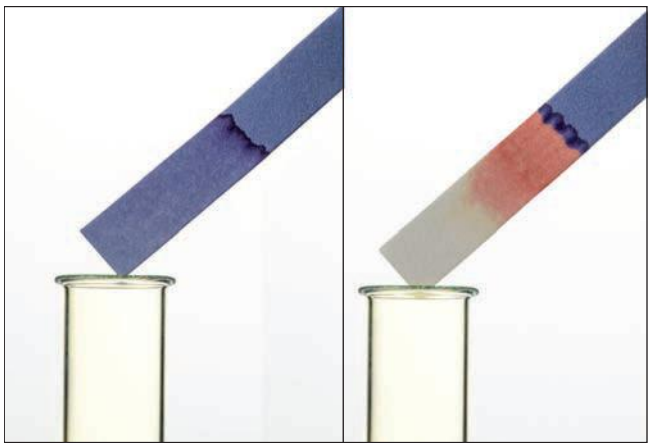

Figure C12.30: Testing for chlorine. Damp blue litmus paper is held over a test-tube of chlorine. The chlorine vapour turns the strip red and then bleaches it white.

If damp red litmus is used for the test for chlorine then it is simply bleached white.

Ammonia

Ammonia (NH_3) is a colourless gas with a distinctive, pungent odour. The standard test for ammonia gas is to use damp red litmus paper. The damp red litmus paper will turn blue. This is because ammonia will dissolve in water to form a weak base (ammonium hydroxide).

Questions

C12.17 A colourless, odourless gas produced a white precipitate when bubbled through limewater.

- **a** What gas was present?
- **b** Give the balanced symbol equation for the reaction between the gas and the limewater (calcium hydroxide).

C12.18 A colourless, odourless gas did not relight a glowing splint and did not turn limewater cloudy. What conclusions can you make about this gas?

C12.05 Acid–base titrations

Titration, a form of **quantitative analysis**, is used to determine the concentration of a wide range of substances. Titrations are used in many industries, including agriculture, food production, cosmetic manufacturing, pharmaceutical companies, water works and mining organisations. Here we will consider the use of titrations in determining the concentrations in an **acid–base titration**.

In an acid–base titration, a specified, fixed volume of base is placed into a conical flask by means of a volumetric pipette and filler. Typical pipette volumes are either 10.0 cm^3 or 25.0 cm^3 and the pipettes used are highly accurate.

The acid is dispensed using a burette, a piece of glassware that gives an accurate but variable volume of liquid. After carefully recording the start volume, the acid is added to the base by opening the tap at the bottom of the burette (Figure C12.31). The burette should be clamped vertically above the conical flask and a white tile may be placed under the conical flask to help see any colour change. The volume added from the burette during a titration is called the **titre** volume.

KEY WORDS

quantitative analysis: the process used to determine the amount or percentage of a substance in a given sample.

acid–base titration: a method of quantitative chemical analysis where an acid is added slowly to a base until it has been neutralised, or vice versa.

titre: the volume of solution added from the burette during a titration.

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Figure C12.31: Performing an acid–base titration using methyl orange as indicator.

To determine the point at which the alkali has been neutralised, acid–base titrations use an indicator. An indicator is a chemical that gives a clear colour change at the end-point for the reaction. Care must be taken to add the acid dropwise from the burette as the end-point is approached. The conical flask must also be swirled to ensure everything is mixed and the reaction is complete. There are many different indicators including methyl orange and thymolphthalein. Methyl orange turns from yellow in basic conditions to red in acidic conditions, whereas thymolphthalein is blue in basic conditions and colourless in acidic conditions (Chapter C7).

When measuring the volume added from the burette it is important to be very precise. Read carefully from the base of the meniscus and to an accuracy of $\pm 0.05\,cm^3$. You should read with your eyes positioned horizontal to the meniscus (Figure C12.32). Two readings need to be taken from the burette: the start volume and end volume. The volume of liquid added from the burette is calculated as the difference between these two values.

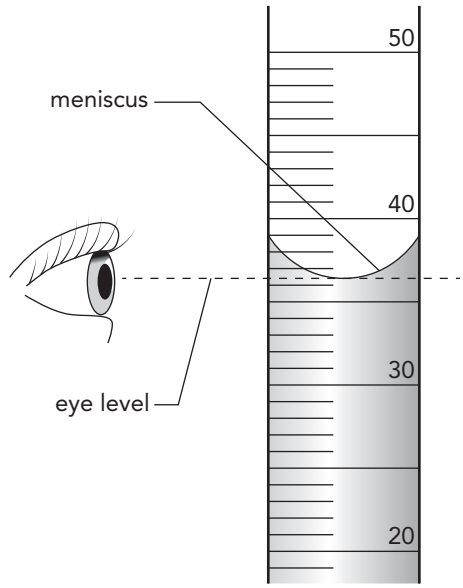

Figure C12.32: How to take an accurate burette reading.

Titrations are repeated until three results within $\pm 0.10\,cm^3$ are obtained. The first run in a titration experiment is a trial or pilot run. As the end-point is unknown, this first run is used to give an approximate titre volume. Any subsequent titrations will be added dropwise as the end-point is approached. A mean titre should then be calculated from the accurate results. See Chapter C12 for details of the calculations required to work out concentration in an acid–base titration.

The titration described here is for a titration involving solutions of an acid and an alkali. However, titrations can also be carried out using an acid solution and an insoluble base.

Questions

C12.19 A titration uses two accurate pieces of glassware. What are they and how do they differ?

C12.20 Why should methyl orange or thymolphthalein be used to detect the end-point of an acid–base titration rather than using universal indicator?

C12.21 When carrying out a titration the method states 'the conical flask must also be swirled'. Why is this important?

C12.22 A titration was repeated five times and the titre volumes were: $12.70\,cm^3$, $12.15\,cm^3$, $12.35\,cm^3$, $12.10\,cm^3$ and $12.10\,cm^3$. If these results were to be used to calculate a concentration, what was the mean titre?

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REFLECTION

To identify different cations, anions and gases you will need to know the results of many different tests. There are different approaches to remembering this type of information:

- You could spend time repeating the information for each test and result or ask your peers to ask you questions.
- You could write a mnemonic (a sentence that helps you to recall a list of words). For example, you may already use OIL RIG as a mnemonic to remind yourself that Oxidation Is Loss (of electrons) Reduction Is Gain (of electrons).
- You might even consider writing a short story:

  In the **Li**thuanian forest was a **red**wood cabin which **Na**talie entered, removing her **yellow** cap. **K**ristoff in his **lilac** jumper sat with a **Ca**t by the **orange–red** glow of the fire. Hidden here are the first four flame colours: Li (red), Na (yellow), K (lilac) and Ca (orange–red).

Which of these approaches do you think works best for you? How could you assess which approach is most effective in learning the standard tests for ions and gases?

PROJECT C12.01 SEPARATIONS ARE US

'Separations Are Us' is a new business that aims to sell technical know-how to chemical companies around the world. Their aim is to help companies purify products through distillation, filtration, crystallisation and chromatography (Figure C12.33).

You have been asked to produce an advertising brochure for the company that summarises each of these processes and that gives some possible applications of each.

As you work through your leaflet/brochure, ensure you meet all of the following criteria:

1. You have included at least four different separation techniques.
2. For each technique you have given a simple diagram to show the apparatus needed.
3. You have explained the chemistry involved in each method.
4. You have outlined what sort of mixture each method can be used to separate.
5. You have discussed some tests that could be carried out to prove the identity of anions and cations present in the products.

You may want to extend your brochure to include information about using melting points as a check for product purity.

Figure C12.33: A technician adjusting the valves on industrial filtration tanks.

SUMMARY

There are different factors involved in the design and planning of an experiment, including choice of apparatus, level of accuracy, variables, sources of error and safety.
The correct apparatus to select when measuring time is a stopwatch or stopclock; temperature, a thermometer; mass, a balance; volume, the appropriate glassware; and pH, universal indicator or a pH meter.
There is a range of different separation and purification techniques, including use of a solvent (to separate two solids), filtration (to separate an insoluble solid from a liquid), crystallisation (to separate a soluble solid from a solution) and simple or fractional distillation (to separate a liquid from a solution or a mixture of liquids).
The correct separation technique needs to be selected for a given mixture.
Melting point and boiling point data can be used to identify substances and assess their purity.
Paper chromatography is a simple separation technique and a chromatogram can be used to determine whether a sample is a pure substance or a mixture.
A reference sample is used to compare samples in chromatography.
An R_f value is a ratio calculated from a chromatogram. It is the distance moved by the substance divided by the distance moved by the solvent front.
Flame tests can be used to identify the presence of metal cations based on the characteristic colour of the flames produced: Li^+(red), Na^+(yellow), K^+(lilac) and Cu^{2+}(blue–green).
Precipitation reactions with aqueous solutions of sodium hydroxide or ammonia can be used to test for the metal aqueous cations Ca^{2+}, Cu^{2+}, Fe^{2+}, Fe^{3+} and Zn^{2+}.
Sodium hydroxide can also be used to test for ammonium ions, which are reduced to ammonia.
To test for anions: carbonate ions are detected by effervescence with dilute acid, which produces carbon dioxide. Halide ions are detected by precipitation reactions with acidified silver nitrate. Sulfate ions are detected by a precipitation reaction with acidified barium nitrate.
Nitrate ions are detected by a redox reaction using aluminium, which produces ammonia gas.
The tests for common gases are: hydrogen gives a squeaky pop with a lit splint; oxygen relights a glowing splint; carbon dioxide turns limewater milky; chlorine bleaches damp litmus paper; and ammonia turns damp red litmus paper blue.
Acid–base titrations are a commonly used form of quantitative analysis, which uses highly accurate glassware (the pipette and burette).
The end-point of a titration is detected by a colour change in an indicator: methyl orange turns from yellow to red (basic to acidic conditions), whereas thymolphthalein turns from blue to colourless (basic to acidic conditions).

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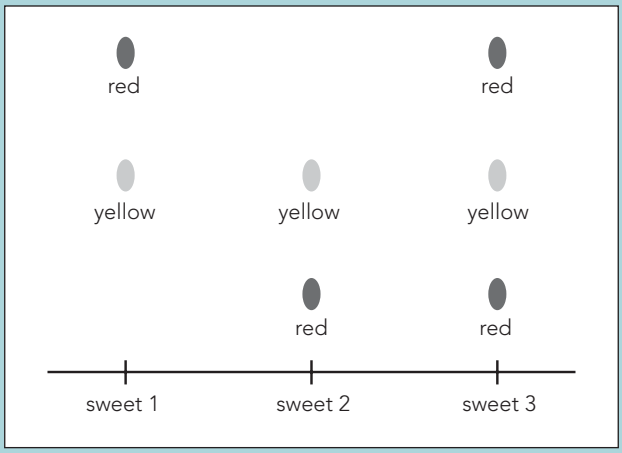
PRACTICE QUESTIONS

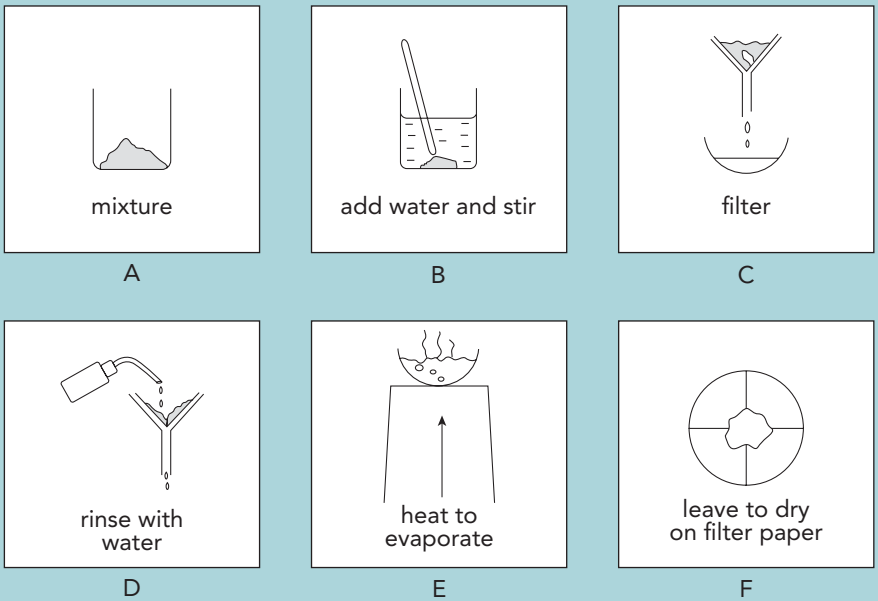
1 Coloured sweets contain edible dyes. These dyes can be separated by chromatography. The figure shows chromatograms obtained from three different orange sweets.



Identify how many different red dyes were present in these orange sweets.

A 4
B 3
C 2
D 7 **[1]**

2 The diagrams A–F in the figure show the stages in an experiment to separate a mixture of copper(II) sulfate and copper(II) oxide and prepare clean dry crystals of copper(II) sulfate.



COMMAND WORD

identify: name/select/recognise.

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CONTINUED

a Identify the two pieces of apparatus drawn in E. **[2]**

b **State** the colour of the solution in beaker B. **[1]**

c **Give** a reason why the mixture was stirred with water and not acid. **[1]**

[Total: 4]

3 Malachite is an ore of copper which contains copper carbonate, $CuCO_3$. You are provided with a large lump of malachite. **Describe** an experiment to obtain a sample of pure copper from this ore. **[6]**

4 The following questions refer to different items of common laboratory apparatus.

a Give a reason why a measuring cylinder might be used instead of a gas jar to collect a gas over water. **[1]**

b State how a Bunsen burner can be adjusted to produce the hottest flame. **[1]**

c State how you know when to stop heating, when crystallising from a solution. **[1]**

[Total: 3]

5 A solution of an unknown salt is tested in two ways. First, excess ammonia solution is added to one portion of the solution and a white precipitate is formed that then re-dissolves. A second portion of the unknown salt is tested with excess sodium hydroxide solution. Again, a white precipitate is formed that re-dissolves.

Identify what metal ion is present in the unknown solution.

A Ca^{2+}

B Fe^{3+}

C Cu^{2+}

D Zn^{2+} **[1]**

6 The table shows some salts and the results of tests carried out on the salts. Copy and complete the table.

Salt	Flame test	Slowly adding excess aqueous sodium hydroxide	Adding acidified silver nitrate
potassium sulfate		no reaction	
	blue–green colour	light blue precipitate formed	cream precipitate
lithium iodide		no reaction	

[5]

7 What *two* tests can you do to prove that a sample of pale-green crystals is iron(II) sulfate? State the tests and give the observed result of each test.

a Test I **[2]**

b Test II **[2]**

[Total: 4]

8 Vinegar contains ethanoic acid and can be made from wine or malt (germinated and dried cereal grains). You are provided with two bottles of vinegar, one bottle of vinegar made from wine and one bottle of vinegar made from malt. Describe an experiment to discover which of these vinegars contains the more concentrated solution of ethanoic acid. **[6]**

COMMAND WORDS

state: express in clear terms.

give: produce an answer from a given source or recall/memory.

describe: state the points of a topic/give characteristics and main features.

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SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
understand the different factors involved in the design and planning of an experiment	C12.01			
name appropriate apparatus for the measurement of time, temperature, mass, volume and pH	C12.01			
state possible advantages/disadvantages for selecting a particular method or piece of apparatus	C12.01			
explain the terms solvent, solute, solution, saturated solution, residue and filtrate	C12.02			
describe how a mixture of solids can be separated by using different solvents	C12.02			
explain how filtration can be used to separate an insoluble compound from a solvent or solution	C12.02			
describe how to crystallise a soluble salt from a solution	C12.02			
explain how simple and fractional distillation can be used to separate mixtures of liquids	C12.02			
identify the most suitable separation technique when given information about the substances present	C12.02			
describe the use of melting and boiling points to determine purity	C12.02			
explain how to carry out a simple paper chromatography to separate coloured compounds	C12.03			
use a chromatogram to compare an unknown to a known sample and deduce whether a substance is pure or a mixture	C12.03			
recall and use the equation to calculate R_f values	C12.03			
give the characteristic colours for the flame test for the metal cations: Li^+, Na^+, K^+ and Cu^{2+}	C12.04			
describe how aqueous solutions of sodium hydroxide or ammonia can be used to identify the cations Ca^{2+}, Cu^{2+}, Fe^{2+}, Fe^{3+} and Zn^{2+}	C12.04			
describe a simple test for the presence of ammonium ions	C12.04			
describe the tests to identify common anions	C12.04			

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CONTINUED

I can	See topic . . .	Needs more work	Almost there	Confident to move on
describe the tests to identify different gases (hydrogen, oxygen, carbon dioxide, chlorine and ammonia)	C12.04			
explain what a burette and a pipette are used for in a titration experiment	C12.05			
describe how to perform an acid–base titration	C12.05			
give the colour changes for methyl orange and thymolphthalein used to identify the end-point of an acid–base titration.	C12.05			

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P1
Motion

All learners study some content in this chapter

IN THIS CHAPTER YOU WILL:

- learn how to take measurements of length, volume and time
- calculate density
- perform experiments to determine the density of an object
- define speed and calculate average speed
- plot and interpret distance–time and speed–time graphs
- work out the distance travelled, from the area under a speed–time graph
- understand that acceleration is a change in speed and the gradient of a speed–time graph
- distinguish between scalar and vector quantities
- define and calculate acceleration, and understand deceleration as a negative acceleration
- use the gradient of a distance–time graph to calculate speed, and the gradient of a speed–time graph to calculate acceleration
- discover the differences between mass and weight
- describe how forces may change the size, shape and motion of a body
- find the resultant of two or more forces acting along the same line

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CONTINUED

- find out about the effect of friction (or air resistance or drag) on a moving object
- learn how force, mass and acceleration are related
- investigate the effect of forces on a spring
- describe and calculate the turning force
- investigate and apply the principle of moments
- describe the conditions needed for an object to be in equilibrium
- perform an experiment to find the centre of mass
- describe how the centre of gravity of an object affects its stability
- relate pressure to force and area, and recall the associated equation $p = \frac{F}{A}$

BEFORE YOU START

In pairs, either make the following measurements or describe how you would make them:

- the length, width and thickness of this book, and then its volume
- the thickness of a sheet of paper that makes up this book
- the length of a journey (for example, on a map) that is not straight
- the volume of liquid which fits into a cup, such as the one shown in Figure P1.01
- the force needed to lift your school bag
- which of the surfaces shown in Figure P1.02 causes more friction.

Figure P1.01: The volume of liquid in a cup can be measured.

Figure P1.02: The force of friction on different surfaces can be measured.

SCIENCE IN CONTEXT P1.01

Around the world in 80 days

The first known circumnavigation (trip around the world) was completed by a Spanish ship on 8 September 1522. It took more than three years. The French writer Jules Verne wrote the book *Le tour du monde en quatre-vingts jours* (which means *Around the World in Eighty Days*) in 1873. In honour of the writer, the Jules Verne Trophy is a prize for the fastest circumnavigation by a yacht. The award is currently held by the yacht IDEC Sport, which completed the journey in just under 41 days in 2017. In 2002, the American Steve Fossett was the first to make a solo circumnavigation in a balloon, without stopping, taking just over 13 days. In 2006, he flew the Virgin Atlantic GlobalFlyer, the first fixed-wing aircraft to go around the world without stopping or refuelling. It took him just under three days (Figure P1.03). Hypersonic jets are being developed that could fly at 1.7 km/s. At this speed, they could circumnavigate the globe in an incredible six and a half hours.

Figure P1.03: The Virgin Atlantic GlobalFlyer passes over the Atlas Mountains.

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Sometimes these epic adventures inspire those who do them to campaign for a better world. The British sailor Ellen MacArthur is just such a person (Figure P1.04). She held the world record for the fastest solo circumnavigation, achieved on 7 February 2005. However, she retired from competitive sailing to set up the Ellen MacArthur Foundation, a charity that works with businesses and in education to accelerate the transition to a circular economy. A circular economy is one in which things should be designed to last a long time and be easy to maintain, repair, reuse or recycle. Therefore, a circular economy would create less waste.

Discussion questions

1 What were the speeds of the six journeys mentioned in the first paragraph? Assume that the Earth's circumference is 40 000 km.

2 What could cause the fastest boat to not win a round-the-world yacht race?

Figure P1.04: Ellen MacArthur celebrates after completing her record solo round-the-world journey on 7 February 2005 in Falmouth, England.

P1.01 Measuring length and volume

In physics, we make measurements of many different lengths, for example, the length of a piece of wire, the height of liquid in a tube, the distance moved by an object, the diameter of a planet or the radius of its orbit. In the laboratory, lengths are often measured using a ruler (such as a metre ruler).

A ruler may measure to the nearest centimetre or the nearest millimetre.

Figure P1.05 shows some things to remember when you use a ruler. The ruler is being used to measure the length of a piece of bent wire.

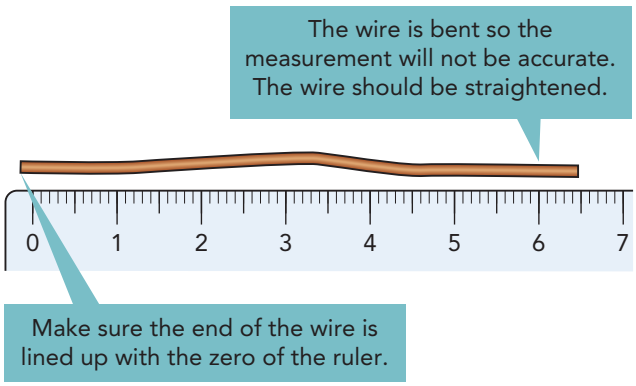

Figure P1.05: Simple measurements still require careful technique, for example, finding the length of a wire.

More measurement techniques

If you have to measure a small length, such as the thickness of a wire, it may be better to measure several thicknesses and then calculate the average. You can use the same approach when measuring something very thin, such as a sheet of paper. Take a stack of 500 sheets and measure its thickness with a ruler (Figure P1.06). Then divide by 500 to find the thickness of one sheet.

For some measurements of length, such as curved lines, it can help to lay a thread along the line. Mark the thread at either end of the line and then lay it along a ruler to find the length. This technique can also be used for measuring the circumference of a cylindrical object such as a wooden rod or a measuring cylinder.

Measuring volumes

Regular shaped solids

For a cube or cuboid, such as a rectangular block, measure the length, width and height of the object and multiply the measurements together (Figure P1.07). For objects of other regular shapes, such as spheres or cylinders, you may have to make one or two measurements and then look up the equation for the **volume**.

KEY WORD

volume: the space occupied by an object.

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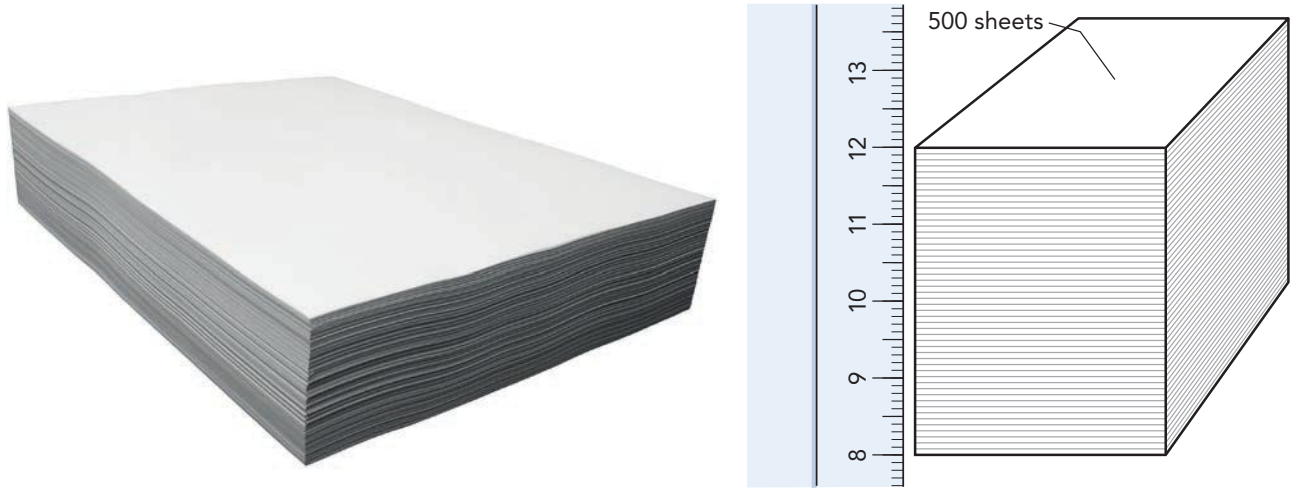

Figure P1.06: Making multiple measurements.

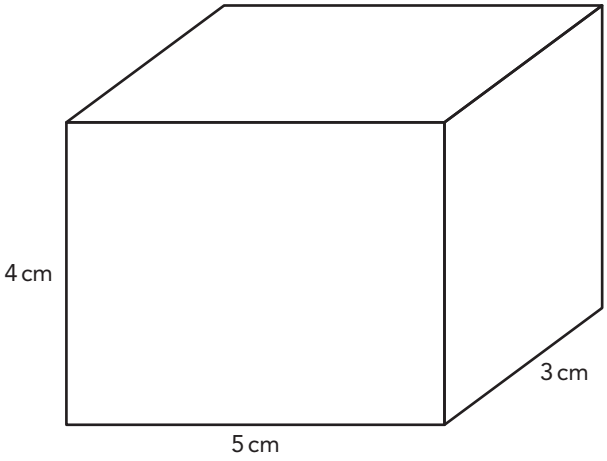

Figure P1.07: Volume = length × width × height = 5 × 3 × 4 = 60 cm^3

Liquids

For liquids, measuring cylinders can be used as shown in Figure P1.08. Remember to have your eye level with the liquid and read the level of the bottom of the **meniscus**. (The meniscus is the curved surface of a liquid.) A 1 litre (or a 1 dm^3) cylinder is not suitable for measuring a small volume such as 5 cm^3. You will get a more accurate answer using a 10 cm^3 cylinder.

Irregular shaped solids

Most objects do not have a regular shape, so we cannot find their volumes simply by measuring the lengths of their sides. Here is how to find the volume of an irregularly shaped object. This technique is known as measuring volume by **displacement**.

- Select a measuring cylinder that the object will easily fit into. Partially fill it with enough water to cover the object (Figure P1.09). Note the volume of the water.
- **Immerse** the object in the water. The level of water in the cylinder will increase, because the object pushes the water out of the way and the only way it can move is upwards. The increase in its volume is equal to the volume of the object.

KEY WORDS

meniscus: curved upper surface of a liquid.

displacement: moving something to another place; for example, water is moved out of the way (upwards) when an object is lowered into it.

immerse: to cover something in a fluid (usually water) so that the object is submerged.

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Figure P1.08: A student measuring the volume of a liquid. Her eyes are level with the scale so that she can accurately measure where the meniscus meets the scale.

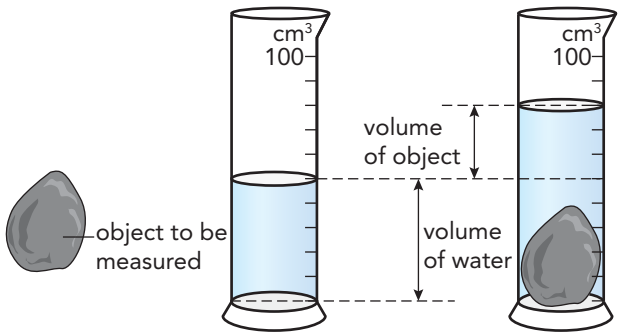

Figure P1.09: Measuring volume by displacement.

Units of length and volume

In physics, we generally use SI units (this is short for Le Système International d'Unités or The International System of Units). The SI unit of length is the metre (m). Table P1.01 shows some alternative units of length, together with some units of volume. Note that the litre and millilitre are not official SI units of volume, and so are not used in this book. One litre (1 l) is the same as 1 dm^3, and one millilitre (1 ml) is the same as 1 cm^3.

Quantity	Units	
length	metre (m)	
	1 decimetre (dm)	= 0.1 m
	1 centimetre (cm)	= 0.01 m
	1 millimetre (mm)	= 0.001 m
	1 micrometre (μm)	= 0.000 001 m
	1 kilometre (km)	= 1000 m
volume	cubic metre (m^3)	
	1 cubic centimetre (cm^3)	= 0.000 001 m^3
	1 cubic decimetre (dm^3)	= 0.001 m^3

Table P1.01: Some units of length and volume in the SI system.

Questions

P1.01 A piece of wood has sides measuring 20 mm, 45 mm and 10 mm.

a State the lengths of the sides in cm.

b Calculate the volume of the block in cm^3.

P1.02 The volume of a piece of wood which floats in water can be measured as shown in Figure P1.10.

a Write bullet points to describe the procedure.

b Find the volume of the wood.

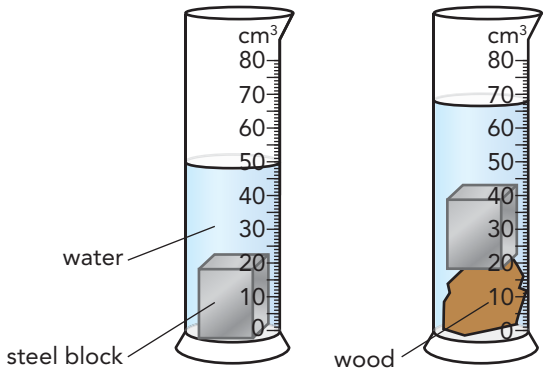

Figure P1.10: Measuring the volume of an object that floats.

P1.03 A stack of paper contains 500 sheets of paper. The stack has dimensions of 0.297 m × 21.0 cm × 50.0 mm.

a What is the thickness of *one* sheet of paper?

b What is the volume of the stack of paper in cm^3?

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P1.02 Density

The **mass** of an object is the quantity (amount) of matter it is made of. Mass is measured in kilograms. But **density** is a property of a material. It tells us how concentrated its mass is.

In everyday speech, we might say that brick is heavier than popcorn (Figure P1.11). We mean that, given equal volumes of brick and popcorn, the brick is heavier. In scientific terms, the density of brick is greater than the density of popcorn.

Figure P1.11: The popcorn and the brick have about the same volume, but the brick has a much bigger mass – the brick is more dense than the popcorn.

KEY WORDS

mass: the quantity of matter a body is composed of; mass causes the object to resist changes in its motion and causes it to have a gravitational attraction for other objects.

density: the ratio of mass to volume for a substance.

Calculating density

We can calculate the density of a material using the equation:

KEY EQUATION

$$\text{density} = \frac{\text{mass}}{\text{volume}}$$

$$\rho = \frac{m}{V}$$

To find the density of a material, we need to know the mass and volume of a sample of the material. The symbol for density is ρ, the Greek letter rho. Density may be measured in grams per cubic centimetre (g/cm^3) or kilograms per cubic metre (kg/m^3).

WORKED EXAMPLE P1.01

A sample of ethanol has a volume of 240 cm^3.

Its mass is 190.0 g.

What is the density of ethanol?

Step 1: Write down what you know and what you want to know.

mass m = 190.0 g

volume V = 240 cm^3

density ρ = ?

Step 2: Write down the equation for density, substitute values and calculate ρ.

Answer

Density of ethanol = 0.79 g/cm^3

Values of density

Some values of density are shown in Table P1.02. Gases have much lower densities than solids or liquids.

An object which is less dense than water will float. Ice is less dense than water, which explains why icebergs float in the sea rather than sinking to the bottom. Only about one-tenth of an iceberg is above the water surface. If any part of an object is above the water surface, then it is less dense than water.

Many materials have a range of densities. Some types of wood, for example, are less dense than water and will float.

	Material	Density / kg/m^3
Gases	air	1.29
	hydrogen	0.09
	helium	0.18
	carbon dioxide	1.98
Liquids	water	1000
	alcohol (ethanol)	790
Solids	ice	920
	wood	400–1200
	polyethene	910–970
	glass	2500–4200
	steel	7500–8100
	lead	11 340
	silver	10 500
	gold	19 300

Table P1.02: Densities of some substances. For gases, these are given at a temperature of 0 °C and normal atmospheric pressure.

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Other types of wood (such as mahogany) are more dense and will sink. The density depends on the nature of the wood (its composition).

It is useful to remember that the density of water is 1000 kg/m^3, 1.0 kg/dm^3 or 1.0 g/cm^3.

Measuring density

The easiest way to determine the density of a substance is to find the mass and volume of a sample of the substance.

EXPERIMENTAL SKILLS P1.01

Finding the density of a liquid

You can determine the density of a liquid by measuring the mass of a measured volume of the liquid and using the equation: density = mass ÷ volume.

You will need:

- measuring cylinder
- balance
- different liquids, such as water and oil.

Safety

Pour liquids carefully and wipe up any spills immediately.

Getting started

You will need to place the cylinder on the balance and zero the balance before you pour in the liquid. Explain why.

Method

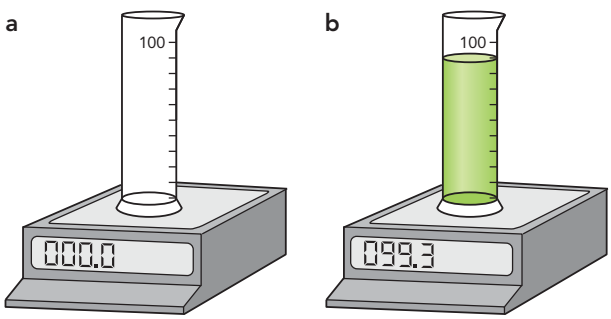

Figure P1.12: Measuring the mass of a liquid.

1. Place a measuring cylinder on a balance. Set the balance to zero (Figure P1.12a).
2. Now pour liquid into the cylinder.
3. Read the volume from the scale on the cylinder (Figure P1.12b).

CONTINUED: P1.01

4. Read the mass from the balance.
5. Record your results in a table.

Liquid	Mass of liquid / g	Volume of liquid / cm^3	Density of liquid / g/cm^3

6. Use the equation density = mass ÷ volume to calculate the density of the liquid.
7. Repeat with other liquids.

Questions

1. List your results in order from most dense to least dense.
2. 80 cm^3 of mercury has a mass of 1080 g. Calculate the density of mercury. How does this compare to the liquids you measured? Why is mercury an unusual liquid?

EXPERIMENTAL SKILLS P1.02

Finding the density of a regular shaped solid

For a solid with a regular shape, you can find its volume by measurement (see Topic P1.01). Find its mass using a balance, then calculate the density.

You will need:

- regular shaped blocks of different materials
- ruler
- balance.

Getting started

Lift the blocks and predict which materials you think will have the highest and lowest densities.

Method

1. Choose a block and record the material it is made of in a table like the one shown below.

Material	Length	Width	Height	Volume	Density

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CONTINUED: P1.02

2 Measure the length, width and height of the block and use these to calculate its volume.

3 Use the balance to determine the mass of the block.

4 Use the equation density = mass ÷ volume to calculate the density.

5 Repeat for other materials.

Finding the density of an irregular shaped solid

WORKED EXAMPLE P1.02

The volume of the object can be determined by the method shown in Figure P1.13, and its mass measured with a balance. The density can then be calculated.

50 cm³ of water are placed in a measuring cylinder. A stone is immersed and the level rises to 70 cm³. The mass of the stone is 52 g. What is the density of the stone?

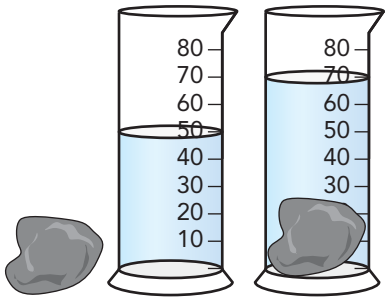

Figure P1.13: Method for determining the volume of an object.

Step 1: Calculate the volume of the stone:

volume of stone = volume of stone and water – volume of water

= 70 – 50

= 20 cm³

Step 2: Calculate the density of the stone

density = mass ÷ volume

= 52 ÷ 20

= 2.6 g/cm³

Questions

P1.04 **a** An object has a mass of 100 g and a volume of 25 cm³. What is its density?

b An object has a volume of 5 m³ and a density of 8000 kg/m³. What is its mass?

P1.05 A brick is shown in Figure P1.14. It has a mass of 2.8 kg.

Figure P1.14: A brick labelled with its dimensions.

a Give the dimensions of the brick in metres.

b Calculate the volume of the brick. Give your answer to two decimal places.

c Calculate the density of the brick.

P1.06 A box full of 35 matches has a mass of 6.77 g. The box itself has a mass of 3.37 g.

a What is the mass of one match in grams?

b A match has dimensions of 42 mm × 2.3 mm × 2.3 mm. What is the volume (in cm³) of each match?

c What is the density of the matches?

d Will the matches float or sink in water?

P1.07 Forty drawing pins (thumb tacks) like those shown in Figure P1.15 have a mass of 17.55 g. What is the volume (in mm³) of one pin when they are made of metal with a density of 8.7 g/cm³?

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Figure P1.15: A pair of drawing pins (thumb tacks).

P1.03 Measuring time

The athletics coach in Figure P1.16 is using his stopwatch to time a hurdler. For a sprinter, a fraction of a second (perhaps just 0.01 s) can make all the difference between winning and coming second or third. It is different in a marathon, where the race lasts for more than two hours and the runners are timed to the nearest second.

Figure P1.16: An athletics coach uses a stopwatch to time a hurdler, who can then learn whether she has improved.

In the laboratory, you might need to record the temperature of a container of water every minute or find out how long an electric current flows for. For measurements like these, stopclocks and stopwatches can be used. You may come across two types of timing device.

An **analogue** clock (Figure P1.17) is like a traditional clock whose hands move round the clock's face. You find the time by looking at where the hands are pointing on the scale. It can be used to measure time intervals to no better than the nearest second.

Figure P1.17: An analogue clock.

A **digital** clock (Figure P1.18) or stopwatch is one that gives a direct reading of the time in numerals. For example, a digital clock might show a time of 9.58 s. A digital clock records time to a **precision** of at least one hundredth of a second. You would never see an analogue watch recording times in the Olympic Games.

Figure P1.18: A digital clock started when the gun fired and stopped 9.58 s later when Usain Bolt crossed the finishing line to win the 100 m at the 2009 World Championships in world record time.

KEY WORDS

analogue: display has hands (or a needle) and is often not very precise.

digital: display shows numbers and is often precise.

precision: when several readings are close together when measuring the same value.

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When studying motion, you may need to measure the time taken for a rapidly moving object to move between two points. In this case, you might use a device called a light gate connected to an electronic timer. This is similar to the way in which runners are timed in major athletics events. An electronic timer starts when the marshal's gun is fired, and stops as the runner crosses the finishing line.

Measuring short intervals of time

Figure P1.19 shows a typical lab pendulum. A mass, called a **plumb bob**, hangs on the end of a string. The string is clamped tightly at the top between two pieces of wood. If you pull the bob gently to one side and release it, the pendulum will swing from side to side.

The time for one **oscillation** of a pendulum (when it swings from left to right and back again) is called its **period**. A single period is usually too short a time to measure accurately. However, because a pendulum swings at a steady rate, you can use a stopwatch to measure the time for a large number of oscillations (perhaps 20 or 50) and calculate the average time per oscillation. Any inaccuracy in the time at which the stopwatch is started and stopped will be much less significant if you measure the total time for a large number of oscillations.

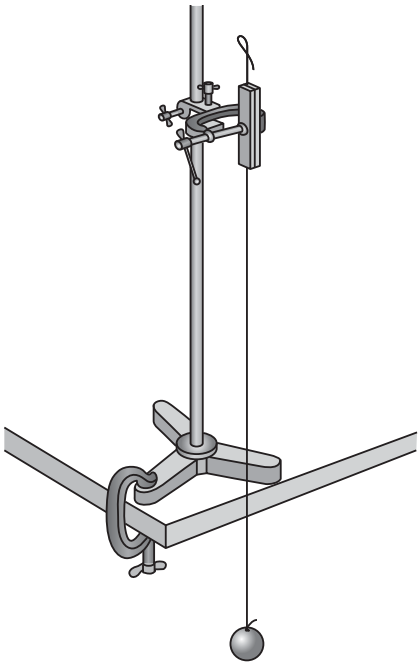

Figure P1.19: A simple pendulum.

KEY WORDS

plumb bob: a mass hanging from a string to define a vertical line.

oscillation: a repetitive motion or vibration.

period: the time for one complete oscillation or wave; the time it takes an object to return to its original position.

Questions

P1.08 Two clocks, one digital and one analogue, were used to measure the time taken by runners in a 100 m race. The analogue clock measured time to the nearest second, and the digital clock measured to the nearest hundredth of a second.

The digital measurements are recorded in Table P1.03.

Runner	Time on digital clock / s	Time on analogue clock
A	9.87	
B	10.34	
C	10.01	

Table P1.03: Runners' times on digital and analogue clocks.

a Make a copy of the table and determine the time which will be shown on the analogue clock for each runner.

b Explain why the analogue clock is not suitable for this task.

P1.09 A student was investigating how the period of a pendulum varied with the length of the string and obtained the results in Table P1.04.

Length of string / m	Time for 20 oscillations / s	Time for 1 oscillation / s
0.00	0.0	
0.20	18.1	
0.40	25.1	
0.60	28.3	
0.80	39.4	
1.00	40.5	
1.20	44.4	
1.40	47.9	

Table P1.04: Times for the oscillation of a pendulum.

a Why did the student record the time for 20 swings?

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b Make a copy of Table P1.04. For each length of the pendulum, calculate the time for one oscillation and record the value in the third column of the table.

c Plot a graph of the period of the pendulum against its length (that is, plot the length of the pendulum on the x-axis).

d Use the graph to work out the length of the pendulum when the period is 2 seconds. This is the length of pendulum used in a grandfather clock.

ACTIVITY P1.01

Using a pendulum as a clock

In 1656, the Dutch scientist Christiaan Huygens invented a clock based on a swinging pendulum. Clocks like these were the most precise in the world until the 1930s. One oscillation of a pendulum is defined as the time it takes for a plumb bob at the bottom of the string to return to its original position (Figure P1.20).

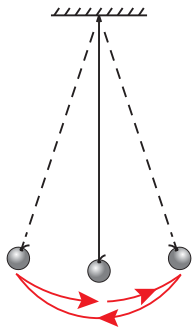

Figure P1.20: One oscillation is when the plumb bob swings one way and then the other and returns to its original position.

Your task is to develop a worksheet so that students can plot a graph of how the period of oscillation of a pendulum varies with the length of the string. They will use the graph to find the length the pendulum needs to be to give a period of one second (useful for a clock). Your worksheet needs to:

- define what an oscillation means (so that a student knows when to start and stop the stopwatch)
- explain why we take the time for 10 or 20 oscillations when we only need the time for one oscillation
- provide a labelled diagram of the assembled apparatus (not just a list of equipment) so that students know how to put the equipment together
- give the method (step-by-step instructions).

CONTINUED

Peer assessment

Swap copies of your worksheet with a classmate. Write down suggestions for any improvements on the worksheet you receive before returning it to its owner. Note down any improvements if you have a class discussion.

Scalar and vector quantities

The measurements you have made so far in this chapter are all **scalar quantities**. A scalar quantity is one which has only magnitude (size). Time, mass, energy and temperature are all examples of scalar quantities.

Some quantities that we measure in physics also have direction. For example, to fully describe a **force** you must give both the size of the force and the direction it acts in. Quantities which have both size and direction are known as **vector quantities**. Force, weight, acceleration and gravitational field strength are all examples of vector quantities.

In physics, the words **speed** and **velocity** have different meanings, although they are closely related: velocity is an object's speed in a particular stated direction (for example, 50 km/h north). Speed is a scalar quantity and velocity is a vector quantity.

KEY WORDS

scalar quantity: is something that has magnitude but no direction.

force: the action of one body on a second body; unbalanced forces cause changes in speed, shape or direction.

vector quantity: has both magnitude (size) and direction.

speed: the distance travelled by an object per unit of time.

velocity: the speed of an object in a stated direction.

P1.04 Understanding speed

If you travel on a major highway or through a large city, it is likely that someone is watching you. Cameras by the side of the road and on overhead road signs keep an eye on traffic as it moves along. Some cameras are there to monitor the flow, so that traffic managers can take action when blockages develop, or when accidents occur. Other cameras

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are equipped with sensors to spot speeding motorists, or those who break the law at traffic lights. In some busy places, traffic police may observe the roads from helicopters.

We will look at how speed is calculated and how graphs can help us understand more about moving objects.

Distance, time and speed

Most methods to determine speed rely on making two measurements:

- the total distance travelled between two points
- the total time taken to travel between these two points.

We can then work out the **average speed** between the two points.

$$\text{average speed} = \frac{\text{total distance travelled}}{\text{total time taken}}$$

KEY WORDS

average speed: the speed calculated from total distance travelled divided by total time taken.

We can use the equation for speed in the definition when an object is travelling at a constant speed. If it travels 10 metres in 1 second, it will travel 20 metres in 2 seconds. Its speed is 10 m/s.

Figure P1.21: Timing a cyclist over a fixed distance. Using a stopwatch involves making judgements as to when the cyclist passes the starting and finishing lines. This can introduce an error into the measurements. An automatic timing system might be better.

We cannot say whether it was travelling at a steady speed, or if its speed was changing. For example, you could use a stopwatch to time a friend cycling over a fixed distance, for example, 100 metres (see Figure P1.21). Dividing distance by time would tell you their average speed, but they might have been speeding up or slowing down along the way.

Table P1.05 shows the different units that may be used in calculations of speed. SI units are the standard units used in physics. The units m/s (metres per second) should remind you that you divide a distance (in metres, m) by a time (in seconds, s) to find speed.

Quantity	SI unit	Other units
distance	metre, m	kilometre, km
time	second, s	hour, h
speed	metres per second, m/s	kilometres per hour, km/h

Table P1.05: Quantities, symbols and units in measurements of speed.

WORKED EXAMPLE P1.03

A cyclist completed a 1500 metre stage of a race in 37.5 s. What was her average speed?

Step 1: Start by writing down what you know, and what you want to know.

distance = 1500 m

time = 37.5 s

speed = ?

Step 2: Now write down the equation.

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

Step 3: Substitute the values of the quantities on the right-hand side.

$$\text{speed} = \frac{1500\,\text{m}}{37.5\,\text{s}}$$

Step 4: Calculate the answer.

speed = 40 m/s

Answer

The cyclist's average speed was 40 m/s.

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Questions

P1.10 **a** What was Usain Bolt's average speed when he achieved his 100 m world record of 9.58 s in 2009?

b How do you know that his top speed must have been higher than this?

P1.11 A cheetah runs 100 m in 3.11 s.
What is its average speed?

P1.12 Information about three trains travelling between stations is shown in Table P1.06.

Vehicle	Distance travelled / km	Time taken / minutes
train A	250	120
train B	72	50
train C	400	150

Table P1.06: Times for train journeys.

a Which train has the highest average speed?

b Which train has the lowest average speed?

Rearranging the equation

It is better to remember one version of an equation and how to rearrange it than to try to remember three different versions.

KEY EQUATION

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

$$v = \frac{s}{t}$$

Beware, s in this equation means distance (or displacement) and not speed. We can rearrange the equation to allow us to calculate distance or time.

For example, a railway signaller might know how fast a train is moving, and needs to be able to predict where it will have reached after a certain length of time:

$$\text{distance} = \text{speed} \times \text{time} \quad \text{or} \quad s = vt$$

Similarly, the crew of an aircraft might want to know how long it will take for their aircraft to travel between two points on its flight path:

$$\text{time} = \frac{\text{distance}}{\text{speed}} \quad \text{or} \quad t = \frac{s}{v}$$

WORKED EXAMPLE P1.04

A satellite is orbiting the Earth at a steady speed of 8.0 km/s (see Figure P1.22). How long will it take to complete a single orbit, a distance of 44 000 km?

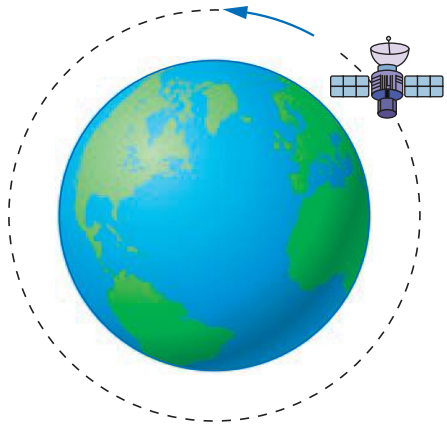

Figure P1.22: A satellite orbiting the Earth.

Step 1: Start by writing down what you know, and what you want to know.

speed (v) = 8.0 km/s

distance (s) = 44 000 km

time (t) = ?

Step 2: Choose the appropriate equation, with the unknown quantity, time, as the subject (on the left-hand side).

$$t = \frac{s}{v}$$

Step 3: Substitute values – it can help to include units.

$$t = \frac{44\,000\,\text{km}}{8.0\,\text{km/s}}$$

Step 4: Perform the calculation.

t = 5500 s

Answer

The time to complete a single orbit (44 000 km) is 5500 s. This is about 92 minutes (5500 ÷ 60 = 91.667). So, the spacecraft takes 92 minutes to orbit the Earth once.

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Worked example P1.04 illustrates the importance of looking at the units. Because speed is in km/s and distance is in km, we do not need to convert to m/s and metres. We would get the same answer if we did the conversion:

$$\text{time} = \frac{44\,000\,000\,\text{m}}{8000\,\text{m/s}}$$
$$= 5500\,\text{s}$$

Questions

P1.13 An aircraft travels 900 metres in 3.0 seconds. Calculate its speed.

P1.14 A car travels 400 km in 3.5 hours. Calculate the speed of the car:

a in km/h

b in m/s.

P1.15 The Voyager spacecraft is moving at 17 000 m/s. How far will it travel in one year? Give your answer in km.

P1.16 How many minutes does it take sunlight to reach us from the Sun? Light travels at 3×10^8 m/s and the Sun is about 144 million km away.

Distance–time graphs

We could describe a journey like this: 'The coach drove away from the bus stop. It travelled at a steady speed along the main road, leaving town. After five minutes, it reached the highway, where it was able to speed up. After ten minutes, it was forced to stop because of traffic.'

We can show the same information in the form of a distance–time graph, as shown in Figure P1.23. This graph is in three sections, corresponding to the three sections of the coach's journey.

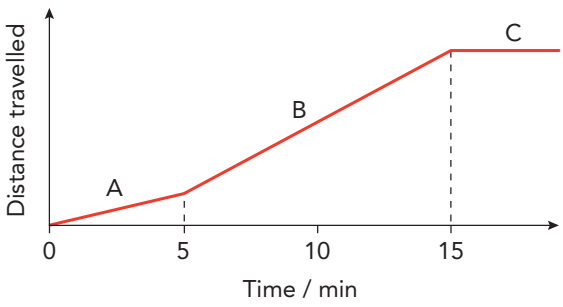

Figure P1.23: A graph to represent the motion of a coach, as described in the text. The slope of the graph tells us about the coach's speed.

In section A, the graph slopes up gently, showing that the coach was travelling at a slow speed.

In section B, the graph becomes steeper. The distance of the coach from its starting point is increasing more rapidly. It is moving faster.

In section C, the graph is flat (horizontal). The distance of the coach from its starting point is not changing. It is stationary.

The slope of the distance–time graph tells us how fast the coach is moving. The steeper the graph, the faster it is moving (the greater its speed). When the graph becomes horizontal, its slope is zero. This tells us that the coach's speed is zero in section C. It is not moving.

Questions

P1.17 A boy runs 300 m in 80 s. He then speeds up and sprints 100 m in 20 s.

a Plot a distance–time graph for the boy's run.

b What is the total distance he runs?

c What is his total time for the run?

d What is the boy's average speed?

P1.18 Figure P1.24 shows the distance–time graph for a woman running a mountain marathon.

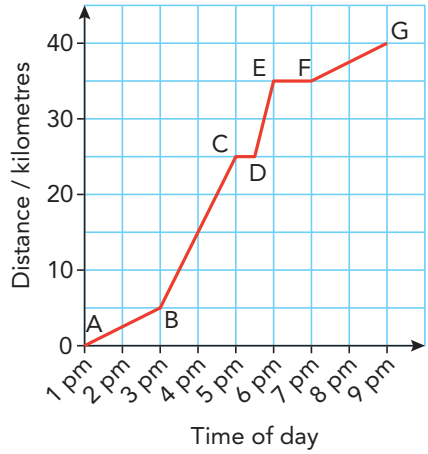

Figure P1.24: Distance–time graph.

a How far did she travel?

b What was her average speed in km/h?

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c How many stops did she make?

d The rules said she had to stop for half an hour for food. When did she take her break?

e Later she stopped to help an injured runner. When did this happen?

f What would her average speed have been if she had not stopped at all?

g What was her highest speed and over what section did this happen?

Finding speed from a distance–time graph

From a distance–time graph, we can find how fast something is moving. Table P1.07 shows information about a car journey between two cities. The car travelled more slowly at some times than at others. It is easier to see this if we present the information as a graph (Figure P1.25).

From the graph, you can see that the car travelled slowly at the start of its journey, and also at the end, when it was travelling through the city. The graph is steeper in the middle section, when it was travelling on the open road between the cities.

The graph also shows how to use the gradient to calculate the car's speed on the open road:

speed = gradient of distance–time graph

More detail is given in Worked example P1.05.

WORKED EXAMPLE P1.05

Use the gradient of the graph in Figure P1.25 to calculate the car's speed on the open road.

Distance travelled / km	Time taken / hours
0	0.0
10	0.4
20	0.8
100	1.8
110	2.3

Table P1.07: Data for a car journey.

CONTINUED

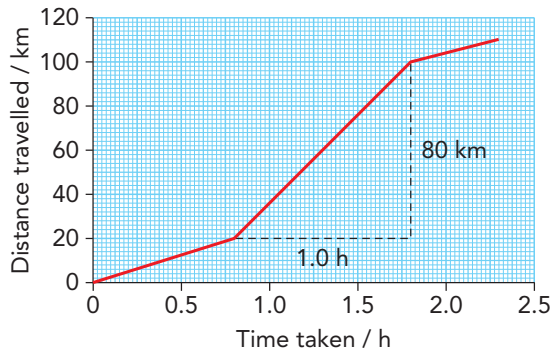

Figure P1.25: Distance–time graph for a car journey.

speed = gradient of distance–time graph

Step 1: Identify the relevant straight section of the graph. Here, we are looking at the straight section in the middle of the graph, where the car's speed was constant.

Step 2: Draw horizontal and vertical lines to complete a right-angled triangle.

Step 3: Calculate the lengths of the sides of the triangle.

Step 4: Divide the vertical height by the horizontal width of the triangle ('up divided by along').

$$\text{vertical height} = 80\,\text{km}$$
$$\text{horizontal width} = 1.0\,\text{h}$$
$$\text{gradient} = \frac{80\,\text{km}}{1.0\,\text{h}}$$
$$= 80\,\text{km/h}$$

Answer

The car's speed was 80 km/h for this section of its journey.

Note: It helps to include units in the calculation because then the answer will automatically have the correct units, in this case, km/h.

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Question

P1.19 Table P1.08 shows information about a train journey.

Station	Distance travelled / km	Time taken / minutes
Hornby	0	0
Kirby Lonsdale	10	30
Ingleton	20	45
Dolphinholme	46	60
Galgate	56	80

Table P1.08: Data for train journeys.

a Use the data in Table P1.08 to plot a distance–time graph for the train.

b Find the train's average speed between Kirby Lonsdale and Dolphinholme. Give your answer in km/h.

P1.05 Understanding acceleration

Acceleration is an increase in speed. Deceleration is a decrease in speed. If an object speeds up quickly we say it has a high acceleration.

Some cars, particularly high-performance ones, are advertised according to how rapidly they can accelerate. An advert may claim that a car goes 'from 0 to 100 km/h in 5 s'. This means that, if the car accelerates at a steady rate, it reaches 20 km/h after 1 s, 40 km/h after 2 s, and so on. We could say that it speeds up by 20 km/h every second. In other words, its acceleration is 20 km/h per second.

So, we say that an object accelerates if its speed increases. Its acceleration tells us the rate at which its speed is changing, that is, the change in speed per unit time.

When an object slows down, its speed is also changing. We say that it is decelerating. Instead of an acceleration, it has a deceleration.

KEY WORD

acceleration: the rate of change of an object's velocity.

Calculating acceleration

Picture an express train setting off from a station on a long, straight track. It may take 300 s to reach a velocity of 300 km/h along the track. Its velocity has increased by 1 km/h each second, and so we say that its acceleration is 1 km/h per second.

These are not very convenient units, although they may help to make it clear what is happening when we talk about acceleration. To calculate an object's acceleration, we need to know two things:

- its change in velocity (how much it speeds up)
- the time taken (how long it takes to speed up).

The acceleration of the object is defined as the change of an object's velocity per unit time. This means we can calculate acceleration by dividing the change in velocity by the time taken for the change.

We can write the equation for acceleration in symbols. We use Δv for change in velocity and Δt for time taken.

KEY EQUATION

$$\text{acceleration} = \frac{\text{change in velocity}}{\text{time taken}}$$

$$a = \frac{\Delta v}{\Delta t}$$

In the example of the express train, the train increases in speed by 300 km/h and time taken is 300 s.

So, for the train,

$$\text{acceleration } a = \frac{300 \text{ km/h}}{300 \text{ s}} = 1 \text{ km/h per second}$$

Units of acceleration

In Worked example P1.06, the units of acceleration are given as m/s^2 (metres per second squared). These are the standard units of acceleration. The calculation shows that the aircraft's velocity increased by 2 m/s every second, or by 2 metres per second per second. It is simplest to write this as 2 m/s^2, but you may prefer to think of it as 2 m/s per second, as this emphasises the meaning of acceleration.

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WORKED EXAMPLE P1.06

An aircraft accelerates from 100 m/s to 300 m/s in 100 s. What is its acceleration?

Step 1: Start by writing down what you know, and what you want to know.

initial velocity $u = 100$ m/s

final velocity $v = 300$ m/s

time $t = 100$ s

acceleration $a = ?$

Step 2: Now calculate the change in velocity.

change in velocity = 300 m/s − 100 m/s
= 200 m/s

Step 3: Substitute into the equation.

$$\text{acceleration} = \frac{\text{change in velocity}}{\text{time taken}}$$
$$= \frac{200\,\text{m/s}}{100\,\text{s}}$$
$$= 2.0\,\text{m/s}^2$$

Alternatively, you could substitute the values of u, v and t directly into the equation.

$$a = \frac{v-u}{\Delta t}$$
$$= \frac{300-100}{100}$$
$$= 2\,\text{m/s}^2$$

Answer

The aircraft's acceleration is 2.0 m/s^2.

Questions

P1.20 Which of the following could not be a unit of acceleration?

km/s^2 mph/s km/s m/s^2

P1.21 A car sets off from traffic lights. It reaches a speed of 21 m/s in 10 s. What is its acceleration?

P1.22 A train, initially moving at 15 m/s, speeds up to 39 m/s in 120 s. What is its acceleration?

Speed–time graphs

Just as we can represent the motion of a moving object with a distance–time graph, we can also represent it in a speed–time graph. A speed–time graph shows how the object's speed changes as it moves. Always check any graph by looking at the axes to see the labels. A speed–time graph has speed on the vertical axis and time on the horizontal axis.

Figure P1.26 shows a speed–time graph for a bus. The graph frequently drops to zero because the bus stops to let people on and off. Then the line slopes up, as the bus accelerates away from the stop. Towards the end of its journey, the bus is moving at a steady speed (horizontal graph), as it does not have to stop. Finally, the graph slopes downwards to zero again as the bus pulls into the terminus and stops.

The slope of the speed–time graph tells us about the bus's acceleration:

- the steeper the slope, the greater the acceleration
- a negative slope means a deceleration (slowing down)
- a horizontal graph (slope = 0) means a constant speed.

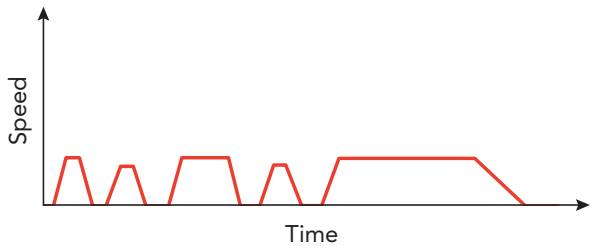

Figure P1.26: A speed–time graph for a bus on a busy route. At first, it has to stop frequently at bus stops. Towards the end of its journey, it maintains a steady speed.

Graphs of different shapes

Speed–time graphs can show us a lot about an object's movement. Was it moving at a steady speed, or speeding up, or slowing down? Was it moving at all?

Figure P1.27 represents a train journey. The graph is in four sections. Each section illustrates a different point:

- A: sloping upwards, so the speed increases and the train is accelerating.
- B: horizontal, so the speed is constant and the train is travelling at a steady speed.
- C: sloping downwards, so the speed decreases and the train is decelerating.
- D: horizontal, so the speed has decreased to zero and the train is stationary.

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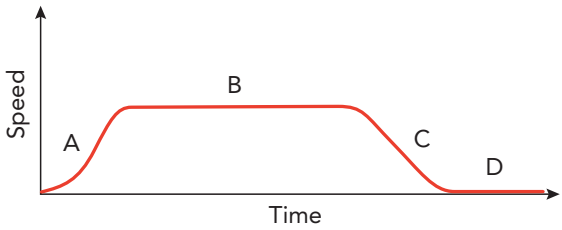

Figure P1.27: An example of a speed–time graph for a train during part of its journey.

The fact that the graph lines are curved in sections A and C tells us that the train's acceleration was changing. If its speed had changed at a steady rate, these lines would have been straight.

Questions

P1.23 Look at the speed–time graph in Figure P1.28.

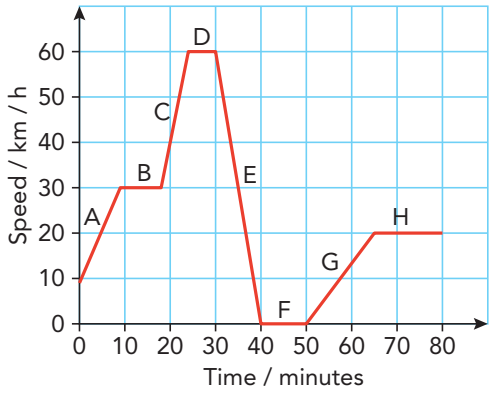

Figure P1.28: A speed-time graph.

Name the sections that represent:

a moving at a steady speed

b speeding up (accelerating)

c being stationary

d slowing down (decelerating).

P1.24 A car is travelling at 20 m/s. The driver sees a hazard. After a reaction time of 0.7 s, she performs an emergency stop by applying the brakes. The car takes a further 3.3 s to come to a stop. Sketch a speed–time graph for her journey from the moment she sees the hazard to the moment she brings her car to a stop. Label the graph with as many details as you can.

Finding distance travelled from a speed–time graph

A speed–time graph represents an object's movement. It tells us about how its speed changes. We can also use the graph to deduce (work out) how far the object travels. To do this, we have to make use of the equation:

distance = area under speed–time graph

To understand this equation, consider Worked examples P1.07, P1.08 and P1.09.

WORKED EXAMPLE P1.07

Calculate the distance you travel when you cycle for 20 s at a constant speed of 10 m/s (see Figure P1.29).

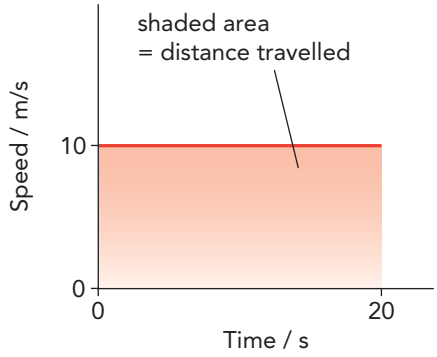

Figure 1.29: Speed–time graph for Worked example P1.07.

Step 1: Distance travelled is the same as the shaded area under the graph. This rectangle is 20 s wide and 10 m/s high, so its area is 10 m/s × 20 s = 200 m.

Step 2: Check using the equation:

distance travelled = speed × time

= 10 m/s × 20 s

= 200 m

Answer

You would travel 200 metres.

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WORKED EXAMPLE P1.08

You set off down a steep ski slope. Your initial speed is 0 m/s. After 10 s you are travelling at 30 m/s (see Figure P1.30). Calculate the distance you travel in this time.

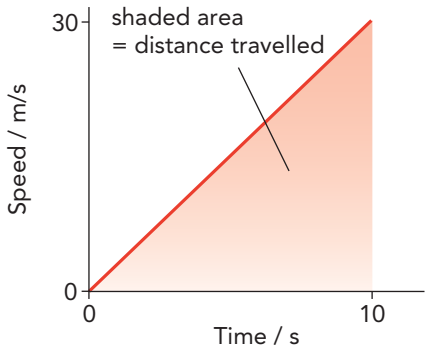

Figure P1.30: Speed–time graph for Worked example P1.08.

Step 1: Distance travelled is the same as the shaded area under the graph. The shape is a triangle with a height of 30 m/s and base of 10 s.

$$\text{area of a triangle} = \frac{1}{2} \times \text{base} \times \text{height}$$

$$\frac{1}{2} \times 10\,\text{s} \times 30\,\text{m/s}$$

$$= 150\,\text{m}$$

Step 2: Check using the equation:

$$\text{average speed} = \frac{\text{initial velocity} + \text{final velocity}}{2}$$

$$= \frac{0\,\text{m/s} + 30\,\text{m/s}}{2}$$

$$= 15\,\text{m/s}$$

$$\text{distance travelled} = \text{average speed} \times \text{time}$$

$$= 15\,\text{m/s} \times 10\,\text{s}$$

$$= 150\,\text{m}$$

Answer

You travel 150 metres.

WORKED EXAMPLE P1.09

A train's motion is represented by the graph in Figure P1.31. Calculate the distance the train travels in 60 s.

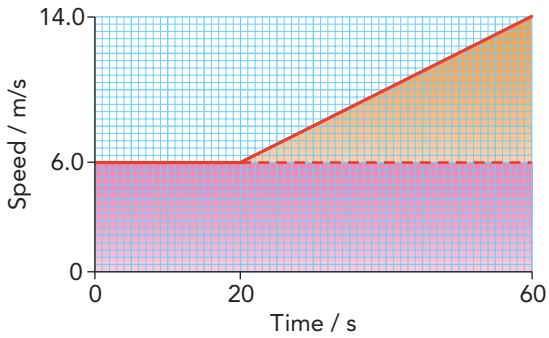

Figure P1.31: Speed–time graph for Worked example P1.09.

Step 1: Distance travelled is the same as the shaded areas under the graph. This graph has two shaded areas: the pink rectangle and the orange triangle.

Step 2: Find the area of the pink rectangle.

It is 60 s wide and 6.0 m/s high, so its area = 60 s × 6.0 m/s = 360 m

(Note: this tells us how far the train would have travelled if it had maintained a constant speed of 6.0 m/s.)

Step 3: Find the area of the orange triangle. It has a base of 40 s and height of 14.0 m/s − 6.0 m/s = 8.0 m/s

$$\text{area of a triangle} = \frac{1}{2} \times \text{base} \times \text{height}$$

$$\frac{1}{2} \times 40\,\text{s} \times 8.0\,\text{m/s}$$

$$= 160\,\text{m}$$

(Note: this tells us the extra distance travelled by the train because it was accelerating.)

Step 4: Add these two areas to find the total area and, therefore, the total distance travelled:

$$\text{total distance travelled} = 360\,\text{m} + 160\,\text{m}$$

$$= 520\,\text{m}$$

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Step 5: Check using the equation:

distance travelled = average speed × time

The train travelled for 20 s at a steady speed of 6.0 m/s, and then for 40 s at an average speed of 10.0 m/s. So:

distance travelled = (6.0 m/s × 20 s) + (10.0 m/s × 40 s)

= 120 m × 400 m

= 520 m

Answer

In 60 s, the train travelled 520 metres.

Questions

P1.25 **a** Draw a speed–time graph to show a car that accelerates uniformly from 6 m/s for 5 s then travels at a steady speed of 12 m/s for 5 s.

b On your graph, shade the area that shows the distance travelled by the car in 10 s.

c Calculate the distance travelled in this time.

P1.26 The speed of a car increases from 12 m/s to 20 m/s in 4 seconds.

a Sketch the speed–time graph.

b Calculate the acceleration.

c Use the graph to work out the distance covered in those 4 seconds.

d Calculate the distance travelled.

e If your answers to parts **c** and **d** are not the same, then work out where you have made a mistake.

Finding acceleration from speed–time graphs

A speed–time graph with a steep slope shows that the speed is changing rapidly – the acceleration is greater. It follows that we can find the acceleration of an object by calculating the gradient of its speed–time graph:

acceleration = gradient of speed–time graph

Three points should be noted:

- The object must be travelling in a straight line; its velocity is changing but its direction is not.
- If the speed–time graph is curved (rather than a straight line), the acceleration is changing.
- If the graph is sloping downwards, the object is decelerating. The gradient of the graph is negative. So a deceleration is a negative acceleration.

WORKED EXAMPLE P1.10

A train travels slowly as it climbs up a long hill. Then it speeds up as it travels down the other side. Table P1.09 shows how its speed changes. Draw a speed–time graph to show these data. Use the graph to calculate the train's acceleration during the second half of its journey.

Time / s	Speed / m/s
0	6.0
10	6.0
20	6.0
30	8.0
40	10.0
50	12.0
60	14.0

Table P1.09: Speed of a train.

Before starting to draw the graph, it is worth looking at the data in the table. The values of speed are given at equal intervals of time (every 10 s). The speed is constant at first (6.0 m/s). Then it increases in equal steps (8.0, 10.0, and so on). In fact, we can see that the speed increases by 2.0 m/s every 10 s. This is enough to tell us that the train's acceleration is 0.2 m/s^2. However, we will follow through the detailed calculation to illustrate how to work out acceleration from a graph.

Step 1: Draw the speed–time graph using the data in Table P1.09; this is shown in Figure P1.32.

The initial horizontal section shows that the train's speed was constant (zero acceleration).

The sloping section shows that the train was then accelerating.

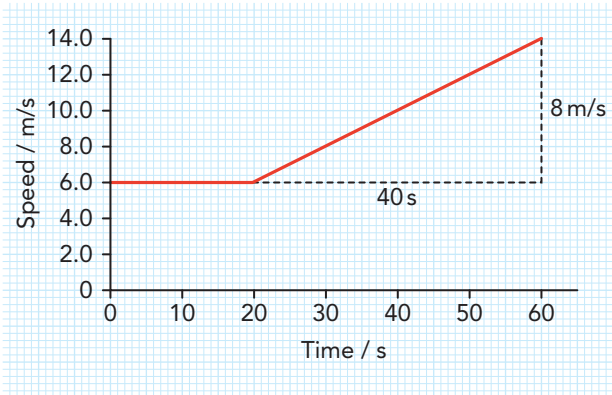

Figure P1.32: Speed–time graph for Worked example P1.10.

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Step 2: Draw horizontal and vertical lines to complete a right-angled triangle.

Step 3: Calculate the lengths of the sides of the triangle.

Step 4: Divide the vertical height by the horizontal width of the triangle ('up divided by along').

acceleration = gradient = vertical height ÷ horizontal width

= 8 m/s ÷ 40 s

= 0.20 m/s^2

Answer

The train's acceleration down the hill is 0.20 m/s^2.

Question

P1.27 A car driver has to do an emergency stop. This is when the driver needs to stop the car in the shortest possible stopping distance. There is a delay between seeing a hazard and applying the brakes. This is due to the reaction time of the driver, sometimes called the thinking time. The distance the car moves in this time (when the car has not changed speed) is the thinking distance. The distance the car moves once the brakes are applied and until the car comes to a stop is the braking distance. The stopping distance = thinking distance + braking distance.

A car is travelling at 20 m/s when the driver sees a hazard. She has a reaction time of 0.7 s and brings her car to a stop 4.0 s after seeing the danger.

a Draw a speed–time graph to represent the car's motion during the 4.0 s described. Assume that the deceleration (negative acceleration) is constant.

b Use the graph to work out the car's deceleration as it slows down.

c Use the graph to find how far the car travels during the 4.0 s described.

P1.06 Mass, weight and gravity

Distinguishing mass and weight

Mass and **weight** are both words we use to say how heavy something is. In physics, it is important to understand the difference between the two quantities, mass and weight.

- The mass of an object is a measure of how much matter an object is made up of. Mass is measured in kilograms.
- The weight of an object is the gravitational force that acts on the object. Weight is a force and so it is measured in newtons.

Gravity and weight

The Earth has a gravitational field around it. This means that any object dropped in this field will experience a force pulling it towards the centre of the Earth and it will fall (see Figure P1.33). All masses have gravitational fields but we only notice it with very large masses such as planets.

Figure P1.33: Gravity was first described by Isaac Newton – possibly after watching an apple fall from a tree. By coincidence, the force of gravity on an apple is about one newton!

The force of **gravity** on the object (its weight) depends on its mass and on how strong the gravitational field is. **Gravitational field strength** is the gravitational force per unit mass (per kilogram). Near the surface of the Earth, the gravitational field strength is about 9.8 newtons per kilogram (N/kg). That is, a mass of 1 kg has a weight of 9.8 N and a mass of 2 kg has a weight of 19.6 N.

KEY WORDS

weight: the downward force of gravity that acts on an object because of its mass.

gravity: the force that exists between any two objects with mass.

gravitational field strength: the gravitational force exerted per unit mass placed at that point.

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Calculating weight

To calculate an object's weight W from its mass m, we multiply by 9.8 – the gravitational force per kilogram, which we call g. We can write this as an equation in words and in symbols:

KEY EQUATION

weight = mass × gravitational field strength

$W = mg$

The Earth's gravitational field strength is 9.8N/kg and this is the value you should use in calculations. Occasionally this is rounded to 10N/kg to make a quick calculation.

The gravitational field strength of an object depends on its mass. The Moon has much less mass than the Earth and so its gravitational field strength is less – approximately 1.6 N/kg (Figure P1.34).

Figure P1.34: The Earth has a much larger mass than the Moon, so the force of gravity is less on the Moon and objects weigh less on the Moon.

WORKED EXAMPLE P1.11

A child has a mass of 40 kg. Calculate their weight:

a on Earth

b on the Moon.

Step 1: Write down what you know and what you want to know.

On Earth:

$m = 40\,\text{kg}$

$g = 9.8\,\text{N/kg}$

$W = ?$

On the Moon:

$m = 40\,\text{kg}$

$g = 1.6\,\text{N/kg}$

$W = ?$

Step 2: Write down the equation you will use:

$W = mg$

Step 3: Substituting into the equation gives:

On Earth: $W = mg = 40 \times 9.8 = 392\,\text{N}$

On the Moon: $W = mg = 40 \times 1.6 = 64\,\text{N}$

Gravity and acceleration

If an object is dropped close to the Earth, it will accelerate because the Earth's gravity pulls it. This is called the **acceleration of free fall** or the **acceleration due to gravity** and is constant at approximately 9.8 m/s².

KEY WORDS

acceleration of free fall (or the acceleration due to gravity): the acceleration of any object falling freely under gravity.

The effect of gravity on a mass

If you drop an object, it falls to the ground. It is difficult to see how a falling object moves. However, a multi-flash photograph can show the pattern of movement when an object falls.

Figure P1.35 shows a ball falling. There are seven images of the ball, taken at equal intervals of time. The ball falls further in each successive time interval. This shows that its speed is increasing – it is accelerating.

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Figure P1.35: The increasing speed of a falling ball is captured in this multi-flash image.

When an object accelerates, there must be a force that is causing it to do so. In this case, the force of gravity is pulling the ball downwards. The name given to the gravitational force acting on an object that has mass is its weight. Because weight is a force, it is measured in newtons (N).

Because the Earth pulls with the same force on every kilogram of matter, every object falls with the same acceleration close to the Earth's surface. If you drop a 5 kg ball and a 1 kg ball at the same time, they will reach the ground at the same time.

The acceleration caused by the pull of the Earth's gravity is called the acceleration of free fall or the acceleration due to gravity. This quantity is given the symbol g, and its value remains approximately constant at 9.8 m/s² close to the surface of the Earth. The acceleration of free fall is equivalent to the gravitational field strength.

Questions

P1.28 List the differences between mass and weight.

P1.29 A bag of sugar has a mass of 1 kg so its weight on Earth is 9.8 N. What can you say about the bag's mass and its weight if you take it:

- **a** to the Moon, where gravity is weaker than on Earth?
- **b** to Jupiter, where gravity is stronger?

P1.30 **a** Look at Table P1.10. Calculate the missing values **i**–**v**. Show your method.

Planet or asteroid	Object on planet or asteroid	Mass of object / kg	Gravitational field strength / N/kg	Weight of object / N
Earth	astronaut	70	9.8	**i**
Moon	astronaut	**ii**	1.60	112.0
Jupiter	tin of beans	0.44	23.0	**iii**
Geographus (asteroid 1620)	bus	**iv**	0.00153	7.650
Toro (asteroid 1685)	astronaut	70	**v**	0.538

Table P1.10: Mass and weight on different planets and asteroids.

- **b** What do you notice about the mass of the astronaut?
- **c** Why does a tin of beans weigh more on Jupiter than a bus weighs on the asteroid Geographus?

P1.07 Forces

Forces may change the shape and size of an object

Forces can change the size and shape of an object. They can stretch, squash, bend or twist an object. Figure P1.36 shows the forces needed for these different ways of deforming an object. You could imagine holding a cylinder of foam rubber, which is easy to deform, and changing its shape in each of these ways.

Foam rubber is good for investigating how things deform, because, when the forces are removed, it springs back to its original shape. Here are two more examples of materials that deform in this way:

- When a football is kicked, it is compressed for a short while (see Figure P1.37a). Then it springs back to its original shape as it pushes itself off the foot of the player who has kicked it. The same is true for a tennis ball when struck by a racket.
- Bungee jumpers rely on the springiness of the rubber rope, which breaks their fall when they jump from a height (see Figure P1.37b). If the rope became permanently stretched, they would stop suddenly at the bottom of their fall, rather than bouncing up and down and gradually coming to a halt.

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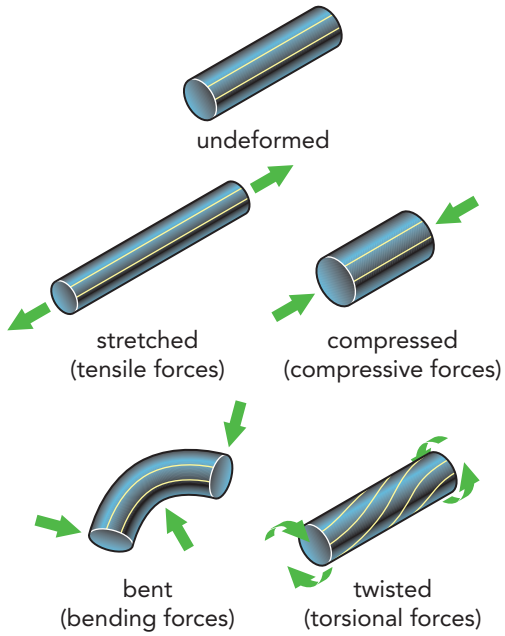

Figure P1.36: Forces can change the size and shape of a solid object. These diagrams show four different ways of deforming a solid object.

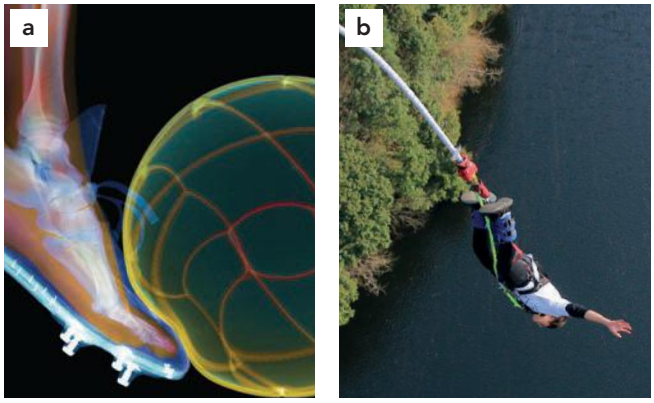

Figure P1.37 a: This X-ray image shows how a football is compressed when it is kicked. It returns to its original shape as it leaves the player's boot. The boot is also compressed slightly but, because it is stiffer than the ball, the effect is less noticeable. **b:** When the bungee cord reaches its maximum extension, it will return to its original length, pulling the bungee jumper upwards.

Some materials are less springy. They become permanently deformed when forces act on them. For example:

- When two cars collide, the metal panels of their bodywork are bent.
- Gold and silver are metals that can be deformed by hammering them (see Figure P1.38). People have known for thousands of years how to shape rings and other ornaments from these precious metals.

Figure P1.38: A Tibetan silversmith making a wrist band. Silver is a relatively soft metal at room temperature, so it can be hammered into shape without the need for heating.

Forces may change the motion of an object

It takes an enormous force to lift a giant space shuttle off its launch pad, and to propel it into space (Figure P1.39). The booster rockets that supply the initial thrust provide a force of several million newtons. As the spacecraft accelerates upwards, the crew experience the sensation of being pressed firmly back into their seats. That is how they know that their craft is accelerating.

Unbalanced forces change motion

One moment, the shuttle is sitting on the ground, stationary. The next moment, it is accelerating upwards, pushed by the force provided by the rockets.

Forces – pushes and pulls – affect objects as they move. The unit used for measuring forces is the *newton* (N). To give an idea of the sizes of various forces, here are some examples:

- You lift an apple. The force needed to lift an apple is roughly one newton (1 N).
- You jump up in the air. Your leg muscles provide the force needed to do this, about 1000 N.
- You reach the motorway in your high-performance car, and press the accelerator pedal. The car accelerates forwards. The engine provides a force of about 5000 N.
- You are crossing the Atlantic in a Boeing 747 jumbo jet. The four engines together provide a thrust of about 500 000 N. In total, that is about half the thrust provided by each of the space shuttle's booster rockets.

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Figure P1.39: A space shuttle accelerating away from its launch pad. The force needed is provided by several rockets. Once each rocket has used all its fuel, it will be jettisoned (dropped), to reduce the mass that is being carried up into space.

Some important forces

Forces appear when two objects interact with each other. Figure P1.40 shows some important forces. Each force is represented by an arrow to show its direction. Usually, the longer the arrow, the bigger the force is. Notice the convention that the arrow usually points away from the object of interest.

Friction

Friction is the force between two surfaces moving, or trying to move, against each other. Friction always acts in the opposite direction to the movement, so it impedes the movement of the objects moving against each other. This has two effects:

- The objects slow down.
- The objects heat up.

A driver who needs to stop quickly will apply the brakes to take advantage of friction between the brake pads and the brake discs. Friction slows the car, but it also heats the brake pads. You can demonstrate the heating effect of friction for yourself, by rubbing your hands together.

The car shown in Figure P1.41 is moving rapidly. The engine is providing a force to accelerate it forwards, but there is another force acting, which tends to slow down the car. This is **air resistance**, a form of friction caused when an object moves through the air. The air drags on the object, producing a force that acts in the opposite direction to the object's motion. There is also resistance to the movement of an object through a liquid – this is usually called drag.

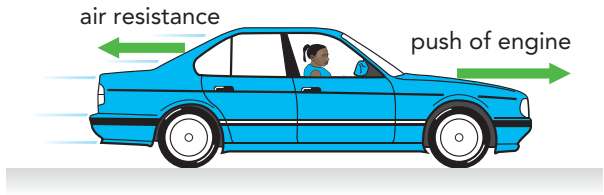
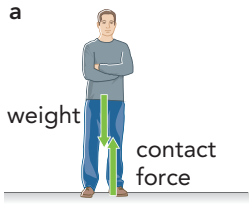


Figure P1.41: A car moves through the air. Air resistance acts in the opposite direction to its motion.

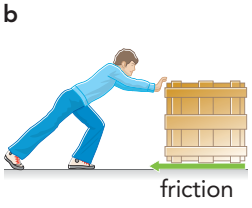
KEY WORDS

friction: the force between two surfaces which may impede motion and produce heating.

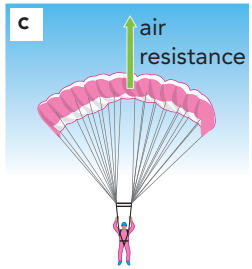
air resistance: friction acting on an object moving through air.



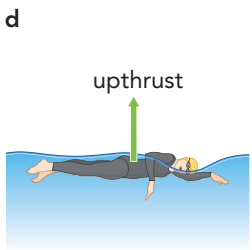
The **weight** of an object is the pull of gravity on it. Weight always acts vertically downwards. When two objects touch, there is a **contact force**. It is the contact force that stops you falling through the floor.



Friction opposes motion. Think about the direction in which an object is moving (or trying to move). Friction acts in the opposite direction.



Air resistance or **drag** is the force of friction when an object moves through air or water.



Upthrust is the upward push of a liquid or gas on an object. The upthrust of water makes you float in the swimming pool.

Figure P1.40: Some common forces.

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Resultant forces

The two forces acting on the car in Figure P1.42a are:

- push of engine = 600 N to the right
- drag of air resistance = 400 N to the left.

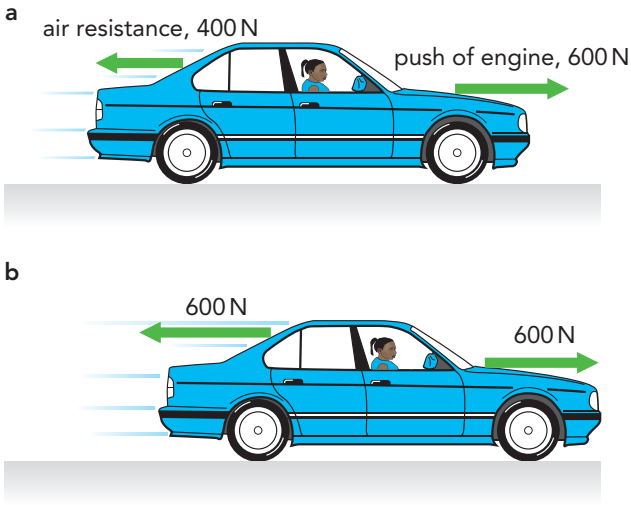

Figure P1.42: A car moves through the air. Air resistance acts in the opposite direction to its motion. **a:** The push of the engine is bigger than the air resistance so the overall force is forward. **b:** When the car is going faster, the air resistance increases so the two forces are equal and opposite meaning there is no overall force on the car.

We can work out the combined effect of these two forces by subtracting one from the other to give the **resultant force** acting on the car. The resultant force is the single force that has the same effect as two or more forces. So, in Figure P1.42a:

$$\text{resultant force} = 600\,\text{N} - 400\,\text{N}$$
$$= 200\,\text{N to the right}$$

This resultant force will make the car accelerate to the right, but not as much as if there was no air resistance.

In Figure P1.42b, the car is moving even faster, and air resistance is greater. Now the two forces cancel each other out. So, in Figure P1.42b:

$$\text{resultant force} = 600\,\text{N} - 600\,\text{N} = 0\,\text{N}$$

We say that the forces on the car are balanced. There is no resultant force and so the car no longer accelerates. It continues at a constant speed in a straight line.

KEY WORDS

resultant force: the single force that has the same effect on a body as two or more forces.

- If no resultant force acts on an object, it will not accelerate; it will remain at rest or it will continue to move at a constant speed in a straight line.
- If an object is at rest or is moving at a constant speed in a straight line, we can say that there is no resultant force acting on it.

Question

P1.31 The forces acting on three objects are shown in Figure P1.43.

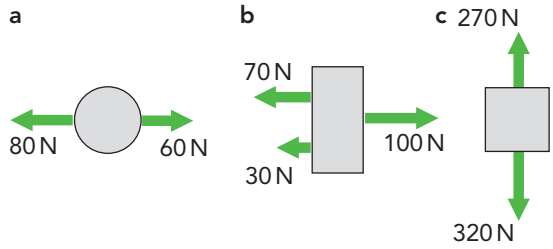

Figure P1.43: Forces acting on three objects.

For each of **a**, **b** and **c**:

i State whether the forces are balanced or unbalanced.

ii If the forces are unbalanced, calculate the resultant force on the object and give its direction.

iii State how the object's motion will change.

P1.08 Force, mass and acceleration

If the resultant force on an object is not zero, its speed will change. It will accelerate or decelerate.

A car driver uses the accelerator pedal to control the car's acceleration. This alters the force provided by the engine. The bigger the force acting on the car, the bigger the acceleration it gives to the car. Doubling the force produces twice the acceleration; three times the force produces three times the acceleration, and so on.

There is another factor that affects the car's acceleration. Suppose the driver fills the boot with a lot of heavy boxes and then collects several children from college. He will notice the difference when he moves away from the traffic lights. The car will not accelerate so readily, because its mass has increased. Similarly, when he applies the brakes, it will not decelerate as readily as before. The mass of the car affects how easily it can accelerate or decelerate. Drivers learn to take account of this.

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The greater the mass of an object, the smaller the acceleration it is given by a particular force.

So, big (more massive) objects are harder to accelerate than small (less massive) ones. If we double the mass of the object, its acceleration for a given force will be halved. We need to double the force to give it the same acceleration.

Force calculations

These relationships between force, mass and acceleration can be combined into an equation:

$$\text{force} = \text{mass} \times \text{acceleration}$$

$$F = ma$$

The quantities involved in this equation, and their units, are summarised in Table P1.11. The unit of force is the newton. Worked examples P1.12 and P1.13 show how to use the equation.

Quantity	Symbol	SI Unit
force	F	netwon, N
mass	m	kilogram, kg
acceleration	a	metres per second squared m/s^2

Table P1.11: The three quantities related by the equation force = mass × acceleration.

WORKED EXAMPLE P1.12

When you strike a tennis ball that another player has hit towards you, you provide a large force to reverse its direction of travel and send it back towards your opponent. You give the ball a large acceleration. What force is needed to give a ball of mass 0.10 kg an acceleration of 500 m/s^2?

Step 1: Write down what you know and what you want to find out:

mass = 0.10 kg

acceleration = 500 m/s^2

force = ?

Step 2: Substitute in the equation to find the force:

force = mass × acceleration

= 0.10 kg × 500 m/s^2

= 50 N

Answer

You need to give the ball a force of 50 N.

Note that mass must be in kg (the base SI unit), not g, if the force is to work out in N.

WORKED EXAMPLE P1.13

An Airbus A380 aircraft (Figure P1.44) has four jet engines, each capable of providing 320 000 N of thrust. The mass of the aircraft is 560 000 kg when loaded. What is the greatest acceleration that the aircraft can achieve?

Figure P1.44: An Airbus A380.

Step 1: Write down what you know and what you want to find out:

force = 4 × 320 000 N = 1 280 000 N (the greatest force provided by all four engines working together)

mass = 560 000 kg

acceleration = ?

Step 2: Substitute in the equation to find the acceleration:

$$\text{acceleration} = \frac{\text{force}}{\text{mass}}$$

$$= \frac{1280\,000\ \text{N}}{560\,000\ \text{kg}}$$

$$= 2.29\ \text{N/kg}$$

Answer

2.29 N/kg is the greatest acceleration the aircraft can achieve.

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Questions

P1.32 Look at Table P1.12. Calculate the missing values **a–d**. Show your working.

Force	Mass	Acceleration / m/s²
a	50 kg	10
112 N	70 kg	**b**
110 kN	**c**	5
d	15 g	10

Table P1.12: Calculations using *F* = *ma*.

P1.33 **a** What is the weight of a brick that has a mass of 2.4 kg?

b The same brick falls with an acceleration of 9.8 m/s². Calculate the force on the brick.

c What can you say about your answers to parts **a** and **b**?

P1.34 A 0.15 kg mass experiences a force of 10 N. What is its acceleration?

P1.09 Stretching springs

To investigate how objects deform when a force is applied, it is simplest to start with a spring. Springs are designed to stretch a long way when a small force is applied, so it is easy to measure how their length changes.

Figure P1.45 shows how to carry out an investigation on stretching a spring. The spring is hung from a rigid clamp,

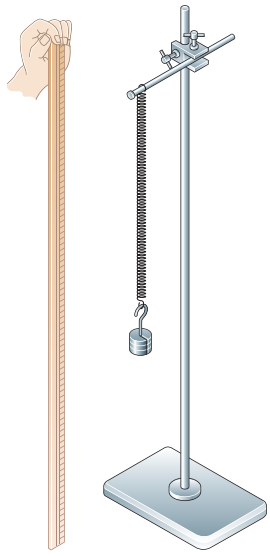

Figure P1.45: Investigating the stretching of a spring.

so that its top end is fixed. Weights are hung on the end of the spring. These are referred to as the **load**. As the load is increased, the spring stretches and its length increases.

Figure P1.46 shows the pattern observed as the load is increased in regular steps. The length of the spring increases (also in regular steps). At this stage, the spring will return to its original length if the load is removed. However, if the load is increased too far, the spring becomes permanently stretched and will not return to its original length.

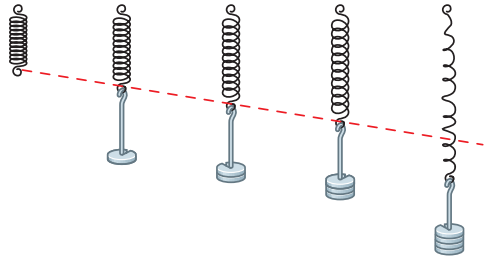

Figure P1.46: Stretching a spring. At first, the spring deforms elastically. It will return to its original length when the load is removed. Eventually, however, the load is so great that the spring is damaged.

Extension of a spring

As the force stretching the spring increases, the spring gets longer. It is important to consider the increase in length of the spring. This quantity is known as the **extension**.

length of stretched spring = original length + extension

This means that, if you double the load that is stretching a spring, the spring will not become twice as long. It is the extension that is doubled.

Table P1.13 shows how to use a table with three columns to record the results of an experiment to stretch a spring. The third column is used to record the value of the extension, which is calculated by subtracting the original length from the value in the second column.

KEY WORDS

load: the force (usually weight) that stretches an object (a spring).

extension: the increased length of an object (for example, a spring) when a load (for example, weight) is attached to it.

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Load / N	Length / cm	Extension / cm
0.0	24.0	0.0
1.0	24.6	0.6
2.0	25.2	1.2
3.0	25.8	1.8
4.0	26.4	2.4
5.0	27.0	3.0
6.0	27.6	3.6
7.0	28.8	4.8
8.0	30.4	6.4

Table P1.13: Results from an experiment to find out how a spring stretches as the load on it is increased.

To see how the extension depends on the load, we draw a load–extension graph (Figure P1.47).

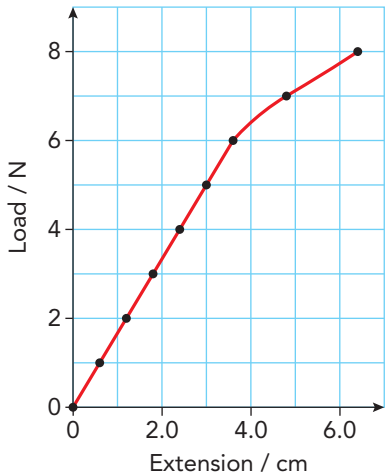

Figure P1.47: A load–extension graph for a spring, based on the data in Table P1.13.

You can see that the graph is in two parts.

- At first, the graph slopes up steadily. This shows that the extension increases in equal steps as the load increases.

  The straight-line graph tells us that the extension of a spring is proportional to the load applied to it. This can be expressed as an equation:

  $$F = kx$$

  In this equation, F is the load (force) stretching the spring, k is the **spring constant** of the spring, and x is the extension of the spring. The spring constant is the force needed to stretch the spring by a unit length (e.g. per cm). The spring constant is a measure of the 'stiffness' of the spring: the stiffer the spring, the bigger the load required to change its length.

KEY EQUATION

$$\text{spring constant} = \frac{\text{force}}{\text{unit extension}}$$

$$k = \frac{F}{x}$$

- Then the graph curves. This happens when the load is so great that the spring has become permanently damaged. It will not return to its original length.

This point at which the graph is no longer a straight line is called the **limit of proportionality**. If the spring is stretched beyond this point, it will be permanently damaged. If the load is removed, the spring will not return all the way to its original length.

You can see the same features in Table P1.13. Look at the third column. At first, the numbers go up in equal steps. The last two steps are bigger.

The behaviour of the spring is represented by the graph in Figure P1.48 and can be described as: the extension of a spring is proportional to the load applied to it, provided the limit of proportionality is not exceeded.

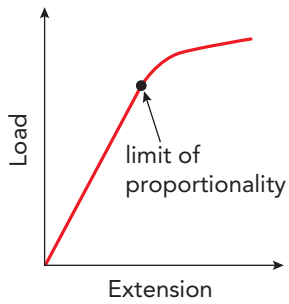

Figure P1.48: A load–extension graph for a spring. Beyond the limit of proportionality, the graph is no longer a straight line, and the spring is permanently deformed.

KEY WORDS

spring constant: the constant of proportionality, the measure of the stiffness of a spring.

limit of proportionality: up to this limit, the extension on a spring is proportional to load.

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WORKED EXAMPLE P1.14

A spring has a spring constant $k = 20\,\text{N/cm}$. What load is needed to produce an extension of 2.5 cm?

Step 1: Write down what you know and what you want to find out.

spring constant $k = 20\,\text{N/cm}$

extension $x = 2.5\,\text{cm}$

load $F = ?$

Step 2: Write down the equation linking these quantities, substitute values and calculate the result.

$F = kx$

$F = 20\,\text{N/cm} \times 2.5\,\text{cm}$

$= 50\,\text{N}$

Answer

A load of 50 N will stretch the spring by 2.5 cm.

EXPERIMENTAL SKILLS P1.03

Investigating springs

Learning how different materials behave when a force is applied to them is very important if they are used to make something. The hull of the RMS *Titanic* was composed of mild steel plates held together by 3 million rivets. When the ship struck an iceberg in 1912 the force broke some of these rivets and this contributed to the ship sinking.

You will investigate how the extension of the spring changes as the load is increased and whether the extension on the spring is proportional to the load.

You will need:

- eye protection
- clamp stand, boss and clamp
- spring and hanger with slotted masses
- G-clamp
- ruler
- plumb bob (a piece of thread with a lump of metal on the end).

Safety

You need to wear eye protection because there is a danger that the spring will fly into someone's eye if it breaks under tension. Place a mat on the floor beneath the masses so that, if the spring snaps, the masses will not damage the floor. Avoid standing on the mat because the masses may land on your feet if the spring snaps.

CONTINUED: P1.03

Getting started

1 Explain the purpose of:
   a the G-clamp
   b the plumb bob.

2 Each slotted weight is 100 g. Calculate what load this represents.

3 Identify the independent (input) and dependent (output) variables.

Method

1 Set up the experiment as shown in Figure P1.49.

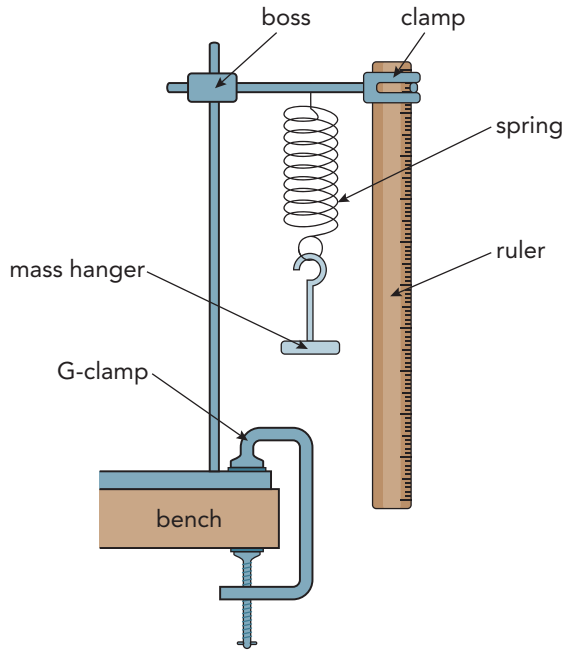

Figure P1.49: Apparatus for investigation.

2 Arrange the ruler with zero at the top. This means that, as the steel spring stretches, the readings on the ruler increase.

3 Use the headings below to draw a results table. Remember to add more rows.

Load on hanger / N	Ruler reading / cm	Spring extension / cm	Does the spring return to original length when unloaded? Y/N

4 Attach your hanger to the bottom of the spring so that the spring hangs vertically.

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CONTINUED: P1.03

5 Record the load as zero and record the reading on the ruler where it lines up with the bottom of the hanger.

6 Add a slotted 100 g mass (equal to a load of 1.0 N) and record the new ruler reading where it lines up with the bottom of the hanger.

7 Remove the mass and record whether the steel spring returns to its original length.

8 Repeat steps 6 and 7, adding another 100 g mass each time until you have filled the table or the spring breaks.

9 Remember, the extension is the difference between the length of the spring with the load attached and the original length when just the hanger was attached. To calculate the spring extension, subtract your ruler reading for a load of 0 N from all of your ruler readings. This means that the spring extension should be zero (0 cm) when the load is zero (0 N).

10 Plot a graph of load against extension (that is, extension on the horizontal axis). Include a title, axis labels and a line of best fit.

Questions

1 Did your graph pass through the origin? If not, did you remember to correct for the original length of the spring?

2 How can you identify where on the graph the force on the steel spring is proportional to the extension? What is the name of the point where this no longer happens to the spring and can you locate it on your graph?

3 What are the values for the load and extension corresponding to the limit of proportionality for your spring?

4 Did the spring continue returning to its original length beyond the limit of proportionality?

Questions

P1.35 A piece of elastic cord is 75 cm long. When it is stretched, its length increases to 97 cm. What is its extension?

P1.36 A spring requires a load of 7.5 N to increase its length by 5.0 cm. What load will give it an extension of 12 cm?

P1.37 A spring has an unstretched length of 13.0 cm. Its spring constant, k is 7.0 N/cm. What load is needed to stretch the spring to a length of 18.0 cm?

P1.38 The results of an experiment to stretch a spring are shown in Table P1.14. Copy the table, adding an extra column for extension. Use the results to plot a load–extension graph. On your graph, mark the limit of proportionality and state the value of the load at that point.

Load / N	Length / m
0.0	1.396
2.6	1.422
5.3	1.448
7.9	1.475
10.6	1.501
13.2	1.536
15.9	1.579

Table P1.14: Results of an experiment in which loads were added to a spring.

P1.10 Turning forces

The moment of a force

Figure P1.50 shows a boy who is trying to open a heavy door by pushing on it. He must make the **turning effect** of his force as big as possible. Where should he push?

Figure P1.50: Opening a door – how can the boy have a big turning effect?

KEY WORDS

turning effect: when a force causes an object to rotate or would make the object rotate if there were no resistive forces.

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First of all, look for the **pivot**. This is the fixed point about which the door will turn. This is the hinge of the door. To open the door, the person must push with as big a force as possible, and as far as possible from the pivot – at the other edge of the door. (That is why the door handle is fitted there.) To have a big turning effect, the person must push hard at right angles to the door. Pushing at a different angle gives a smaller turning effect.

The quantity that tells us the turning effect of a force about a pivot is its **moment**.

- The moment of a force is bigger if the force is bigger.
- The moment of a force is bigger if it acts further from the pivot.
- The moment of a force is greatest if it acts at 90° to the object it acts on.

Making use of turning effects

Figure P1.51 shows how understanding moments can be useful.

a

b

Figure P1.51: Understanding moments can help in some difficult tasks. **a:** The crowbar helps the girl to lift the heavy load. **b:** The man can carry the weight more easily using the wheelbarrow.

When using a crowbar to lift a heavy rock, pull near the end of the bar, and at 90°, to have the biggest possible turning effect.

When lifting a load in a wheelbarrow, the long handles help to increase the moment of the lifting force.

KEY WORDS

pivot: the fixed point about which a lever turns; also known as the fulcrum.

moment: the turning effect of a force about a pivot, given by force × perpendicular distance from the pivot.

Calculating moments

We have seen that the greater a force and the further it acts from the pivot, the greater is its moment. We can write an equation for calculating the moment of a force like this:

KEY EQUATION

$$\text{moment of a force} = \text{force} \times \text{perpendicular distance from the pivot}$$

Now let us consider the unit of moment. Since moment is a force (N) multiplied by a distance (m), its unit is simply the newton metre (N m). There is no special name for this unit in the SI system. Take care: if distances are given in cm, the unit of moment will be N cm. Take care not to mix these different units (N m and N cm) in a single calculation.

Figure P1.52 shows an example. The 40 N force is 2.0 metres from the pivot, so:

$$\text{moment of force} = 40\,\text{N} \times 2.0\,\text{m} = 80\,\text{N m}$$

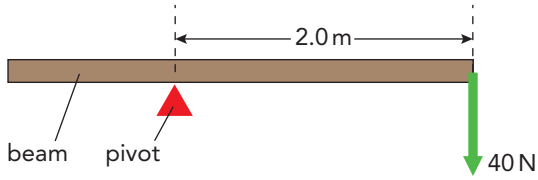

Figure P1.52: Calculating the moment of a force.

Questions

P1.39 Write down, in words, the equation for finding the moment of a force about a point, stating the units for each quantity.

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P1.40 A bolt is tightened by applying a turning force of 30 N to the end of the spanner (Figure P1.53).

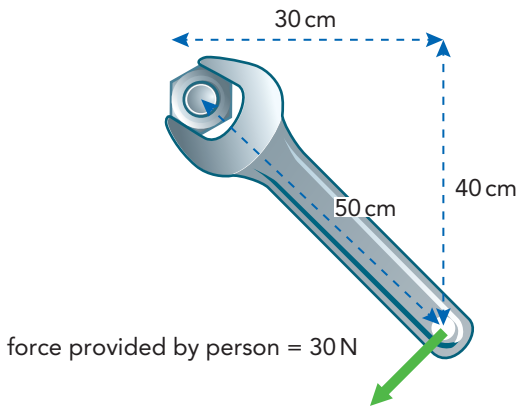

Figure P1.53: A turning force of 30 N is applied.

a Which of the three distance measurements should you use to calculate the moment?

b Use this distance to calculate the moment.

Equilibrium

When things are described as being in **equilibrium**, it means that two or more things are balanced. When a beam, such as the see-saw in Figure P1.54 is balanced, we say that it is in equilibrium. When an object is in equilibrium:

- the forces on it must be balanced (no resultant force)
- the turning effects of the forces on it must also be balanced (no resultant turning effect).

When a resultant force acts on an object, it will start to move off in the direction of the resultant force. If there is a resultant turning effect, it will start to rotate.

Figure P1.54 shows a small child sitting on the left-hand end of a see-saw. Her weight causes an **anticlockwise** moment. This on its own would cause her to move down. If her father pushes down with an equal **clockwise** moment, the see-saw will be in equilibrium and the girl will not move.

KEY WORDS

equilibrium: when no resultant force and no resultant moment act on a body.

anticlockwise: turning in the opposite direction to the hands on a clock.

clockwise: turning in the same direction as the hands on a clock.

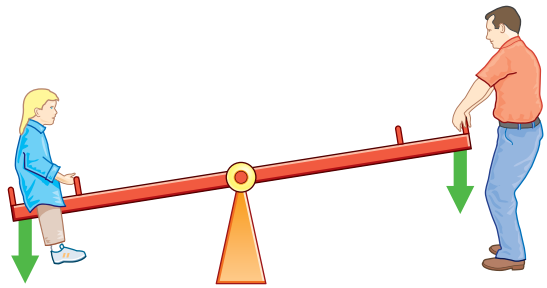

Figure P1.54: When the moments on the see-saw balance, there is no resultant moment and the see-saw is in equilibrium.

Questions

P1.41 Choose the correct option in the following statements.

a The moment of a force is bigger if the force is **smaller / bigger**.

b The moment of a force is bigger if it acts **closer to / further from** the pivot.

c The moment of a force is greatest if it acts at **0°/ 45°/ 90°** to the object it acts on.

P1.42 Three different forces are pulling on a heavy trapdoor (Figure P1.55). Which force will have the biggest turning effect? Explain your answer.

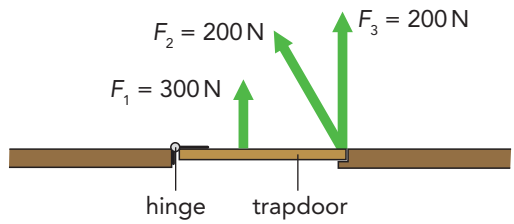

Figure P1.55: Forces providing the turning effect needed to open a trapdoor.

P1.43 Explain why somebody would use a spanner with a longer handle if they needed to undo a tight bolt.

Balancing a beam

Look back at Figure P1.54, where a father and his daughter are playing on a see-saw. On her own, she would make the see-saw turn anticlockwise; her weight has an anticlockwise moment. To make the see-saw balance, her father needs to push down on the right-hand end of the see-saw, applying a clockwise moment.

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The idea that an object is balanced when clockwise and anticlockwise moments are equal is known as the **principle of moments**. We can use this principle to find the value of an unknown force or distance, as shown in Worked example P1.15.

KEY WORDS

principle of moments: when an object is in equilibrium, the sum of anticlockwise moments about any point equals the sum of clockwise moments about the same point.

WORKED EXAMPLE P1.15

The daughter in Figure P1.54 has a weight of 500 N and is sitting 2.0 metres to the left of the pivot. Her father has a weight of 800 N. How far to the right of the pivot should he sit so that the see-saw is balanced?

Step 1: Write down what you know and what you want to find out.

anticlockwise force = 500 N; distance = 2.0 m

clockwise force = 800 N

distance = ?

Step 2: Since the see-saw has to be in equilibrium, we can write:

total anticlockwise moment = total clockwise moment

Step 3: Substitute in the values from step 1, and solve.

$500\,\text{N} \times 2.0\,\text{m} = 800\,\text{N} \times \text{perpendicular distance}$

$1000\,\text{Nm} = 800\,\text{N} \times \text{perpendicular distance}$

$$\text{perpendicular distance} = \frac{1000\,\text{Nm}}{800\,\text{N}} = 1.25\,\text{m}$$

Answer

The father needs to sit 1.25 m to the right of the pivot so that the see-saw is balanced.

Questions

P1.44 A metre ruler balances at its midpoint. Calculate the force F in Figure P1.56.

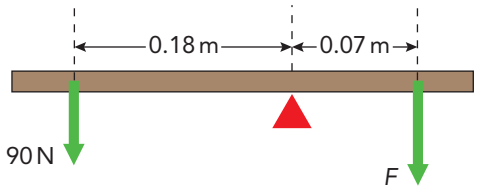

Figure P1.56: A metre rule with forces applied to each side of the pivot.

P1.45 A boy of mass 60 kg, and his sister of mass 49 kg, play on a see-saw pivoted at its centre. If the boy sits 2.7 metres from the pivot of the see-saw, how far from the other side of the pivot must the girl sit to make the see-saw balance?

ACTIVITY P1.02

Understanding the shadoof

The Ancient Egyptians used the shadoof to lift water and irrigate the land. It is still in use today (see Figure P1.57).

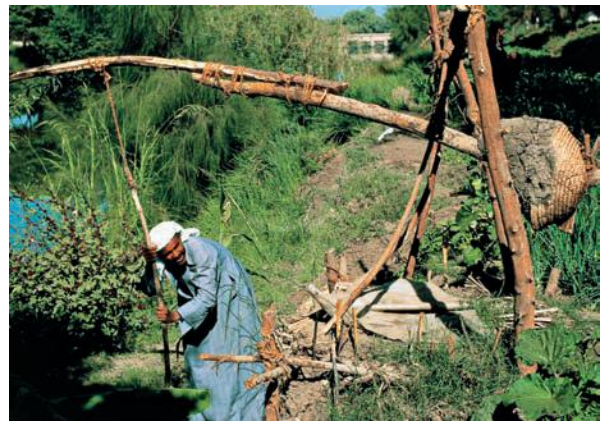

Figure P1.57: A Sudanese man irrigates his land using a shadoof.

The shadoof has a counterweight at the short end and a bucket at the long end of a beam. It takes as much effort to move the bucket down as it does to pull it up.

Spend one minute thinking on your own, one minute of discussion with your neighbour and then be prepared to share your answers to Question 1 with the class.

Questions

1 a What is the advantage of making it take as much effort to push the bucket down as it does to pull it up?

b Explain how the shadoof does this.

2 Draw a diagram of the shadoof and include the pivot, the counterweight and the forces acting on it. You could estimate the lengths of the beam and assume that the counterweight has a weight of 150 N.

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Stability and centre of gravity

People are tall and thin, like a pencil standing on end. Unlike a pencil, we do not topple over when touched by the slightest push. We are able to remain upright, and to walk, because we make continual adjustments to the positions of our limbs and body. We need considerable brain power to control our muscles for this. The advantage is that, with our eyes about a metre higher than if we were on all-fours, we can see much more of the world.

Circus artistes such as tightrope walkers and high-wire artistes (Figure P1.58) have developed the skill of remaining upright to a high degree. They use items such as poles or parasols to help them maintain their balance. The idea of moments can help us to understand why some objects are **stable** while others are more likely to topple over.

Figure P1.58: This high-wire artiste is using a long pole to maintain her stability on the wire. If she senses that her weight is slightly too far to the left, she can redress the balance by moving the pole to the right. Frequent, small adjustments allow her to walk smoothly along the wire.

A tall glass can be knocked over easily – it is **unstable**. Figure P1.59 shows what happens if the glass is tilted.

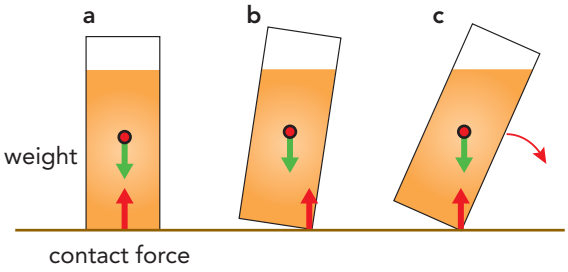

Figure P1.59: A tall glass is easily toppled. Once the line of action of its weight is beyond the edge of the base the glass tips right over.

In Figure P1.59a, the glass is upright. Its weight acts downwards and the contact force of the table acts upwards. The two forces are in line, and the glass is in equilibrium.

In Figure P1.59b, the glass is tilted slightly to the right, and the forces are no longer in line. There is a pivot at the point where the base of the glass is in contact with the table. The line of the glass's weight is to the left of this pivot, so it has an anticlockwise moment, which tends to tip the glass back to its upright position.

In Figure P1.59c, the glass is tipped further. Its weight acts to the right of the pivot, and has a clockwise moment, which makes the glass tip right over.

Centre of gravity

In Figure P1.59, the weight of the glass is represented by an arrow starting at a point inside the liquid. Why is this? The reason is that the glass behaves as if all of its mass were concentrated at this point, known as the **centre of gravity**. The force of gravity acts on the mass of the glass. Each bit of the glass is pulled by the Earth's gravity. However, rather than drawing lots of weight arrows, one for each bit of the glass, it is simpler to draw a single arrow acting through the centre of gravity.

Figure P1.60 shows the position of the centre of gravity for several objects. A person is fairly symmetrical, so their centre of gravity must lie somewhere on the axis of symmetry. (This is because half of their mass is on one side of the axis, and half on the other.) The centre of gravity is in the middle of the body, roughly level with the navel. A ball is much more symmetrical, and its centre of gravity is at its centre.

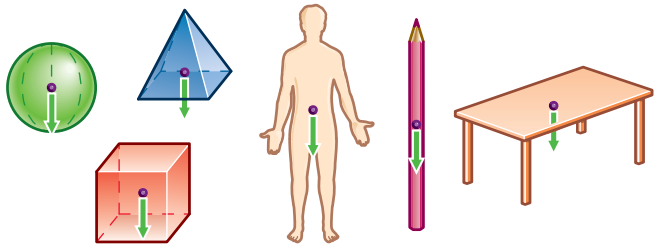

Figure P1.60: The weight of an object acts through its centre of gravity. Symmetry can help to judge where the centre of gravity lies. An object's weight can be considered to act through this point. Note that, for the table, its centre of gravity is in the air below the table top.

KEY WORDS

stable: an object that is unlikely to topple over, often because it has a low centre of gravity and a wide base.

unstable: an object that is likely to topple over, often because it has a high centre of gravity and a narrow base.

centre of gravity: all the mass of an object could be located here and the object would behave the same (when ignoring any spin).

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For an object to be stable, it should have a low centre of gravity and a wide base. The pyramid in Figure P1.60 is an example of this. The high-wire artiste shown in Figure P1.58 has to adjust her position so that her centre of gravity remains above her base, which is the point where her feet make contact with the wire.

Finding the centre of gravity

Balancing is the clue to finding an object's centre of gravity (see Figure P1.61).

Figure P1.61: The pencil balances at its centre, so this must be the centre of gravity.

The procedure for finding the centre of gravity of a more irregularly shaped object is shown in Figure P1.62. In this case, the object is a piece of card, described as a plane **lamina**.

The card is suspended from a pin. If it is free to move, it hangs with its centre of gravity below the point of suspension. This is because its weight pulls it round until the weight and the contact force at the pin are lined up. Then there is no moment about the pin. A plumb bob is used to mark a vertical line below the pin. The centre of gravity must lie on this line.

The process is repeated for two more pinholes. Now there are three lines on the card, and the centre of gravity must lie on all of them, that is, at the point where they intersect. Two lines might have been enough, but it is advisable to use at least three points to reveal any inaccuracies.

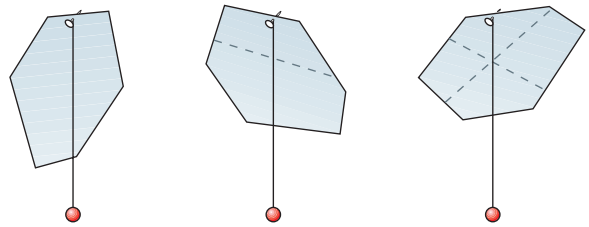

Figure P1.62: Finding the centre of gravity of an irregularly shaped piece of card. The card hangs freely from the pin. The centre of gravity must lie on the line indicated by the plumb bob hanging from the pin. Three lines are enough to find the centre of gravity.

KEY WORD

lamina: flat two-dimensional shape.

EXPERIMENTAL SKILLS P1.04

Centre of gravity of a plane lamina

You will investigate a technique for finding the centre of gravity of a piece of rectangular card. Once you gain confidence that the technique works, you will apply it to an irregular shape, perhaps the map of your country. Locating the centre of gravity of a body is important when considering its stability.

You will need:

- at least two pieces of card
- a hole punch
- a pencil
- a pair of scissors
- a ruler
- a clamp stand and boss
- a pin (or short thin metal rod)
- a length of string with a weight (plumb bob) attached.

Safety

The pin and the scissors should be handled with care to avoid cutting someone. Wear eye protection if using a pin (as opposed to a thin metal rod). Ensure that the pin is not at eye height and is pointing away from the edge of the bench.

Getting started

- Predict where the centre of gravity is located on the rectangular lamina.
- Predict where the centre of gravity is located on the shape you propose.
- Can you suggest shapes where the centre of gravity would not be on the card?

Method: Part 1

Find the centre of gravity of a rectangular sheet of card. This is your lamina.

1 Use the hole punch to make three holes far apart around the edge of the lamina.

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CONTINUED: P1.04

2 Fix the pin horizontally in the clamp.

3 Using one hole, hang the lamina from the pin. Make sure that it can swing freely.

4 Hang the string from the pin so that the weight makes it hang vertically. Mark two points on the lamina along the length of the string.

5 Repeat steps 3 and 4 using the other two holes.

6 Lay the lamina on the bench and, using a ruler, draw lines joining each pair of points. Where the lines cross is the centre of gravity of the lamina. It should be where the lines of symmetry coincide but, if the three lines cross exactly at a point, you have done well!

Method: Part 2

Repeat Part 1 after you have cut a shape out of the lamina. See if you can get a map of your country printed on the card so that you can find its centre of gravity.

Questions

1 Did the three lines you drew intersect at the same point?

2 If the three lines did not intersect at the same point, how did you decide where the centre of gravity is located?

3 If the three lines did not intersect at the same point, how much confidence do you have in the location you have chosen?

4 Suggest a way of checking that you have located (found) the centre of gravity.

5 Explain why the centre of gravity of the lamina lies on a vertical line below the pin (pivot).

Peer assessment

Swap your work with a partner for Experimental skills P1.04.

Give them a smiley face for the following:

- three neatly drawn and closely intersecting lines on their rectangular lamina (as this shows careful experimental technique)
- three closely intersecting lines on their irregular shape
- correct answers to the Getting started questions
- a clear and correct explanation of why the centre of gravity is vertically below the pivot.

Finally, discuss anything that you can learn from each other.

Questions

P1.46 On a copy of the shapes below in Figure P1.63, mark the centre of gravity for each with an X. Where possible, show lines that helped you locate the centre of gravity.

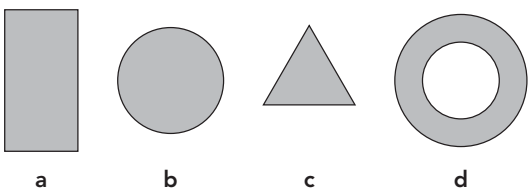

Figure P1.63: Laminar shapes.

P1.47 Buses and other vehicles have to be tilt-tested to an angle of at least 28 degrees from the vertical before they can carry passengers.

a Use the ideas of stability and centre of gravity to explain why either bus in Figure P1.64 would topple over if tilted any further. You can draw on copies of the diagrams to help with your explanation.

b Explain how the stability of the bus would be affected by having more passengers on the upper deck.

c Explain why, for the purposes of the tilt-test, bags of sand are only put on the top deck of bus B and not the lower deck.

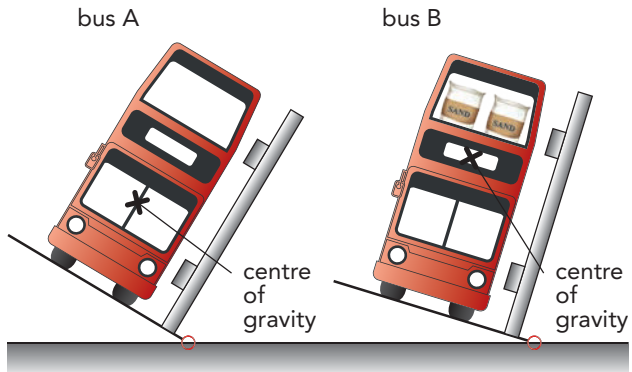

Figure P1.64: Both of these double-decker buses would topple over if tilted any further.

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P1.11 Pressure

Consider the two shoes shown in Figure P1.65. Imagine the owner of the shoes stepping on your foot in each of the shoes. Her weight does not change so the force on your foot will be the same each time. However, it will hurt much more if she wears the stiletto heel.

This is because the stiletto heel has a very small area so all her weight will be concentrated in a very small area of your foot. The force is the same, but the **pressure** is much higher.

Figure P1.65: Stiletto heels have a very small surface area. ('Stiletto' is an Italian word meaning a small and murderous dagger.) Such narrow heels can damage floors, and dance halls often have notices requiring shoes with such heels to be removed.

Spreading a force over a large area will decrease the pressure. Skis have a much larger area than feet, so skiers do not sink into soft snow.

Question

P1.48 Explain the following:

a Tractors have much wider tyres than cars.

b A knife will cut much better when it is sharpened.

Calculating pressure

A large force pressing on a small area gives a high pressure. We can think of pressure as the force per unit area acting on a surface, and we can write an equation for pressure, as shown:

$$\text{pressure} = \frac{\text{force}}{\text{area}}$$

$$p = \frac{F}{A}$$

Now let us consider the unit of pressure. If force, F, is measured in newtons (N) and area, A, is in square metres (m^2), then pressure, p, is in newtons per square metre (N/m^2). In the SI system of units, this is given the name **pascal (Pa)**. It is equivalent to one newton per square metre ($1\ N/m^2$).

KEY WORDS

pressure: the force acting per unit area at right angles to a surface.

pascal (Pa): the SI unit of pressure, equivalent to one newton per square metre; $1\ Pa = 1\ N/m^2$.

WORKED EXAMPLE P1.16

Calculate the pressure exerted by a dancer weighing 600 N standing on a single heel of area $1\ cm^2$. The surface of the dance floor is broken by pressures over 5 million pascals (5.0 MPa). Will it be damaged by the dancer?

Step 1: To calculate the pressure, we need to know the force, and the area on which the force acts, in m^2.

force $F = 600\ N$

area $A = 1\ cm^2 = 0.0001\ m^2$

Step 2: Now we can calculate the pressure p.

$$p = \frac{F}{A}$$

$$= \frac{600\ N}{0.0001\ m^2}$$

$$= 6\,000\,000\ Pa$$

$$= 6.0\ MPa$$

Answer

The pressure is 6.0×10^6 Pa, or 6.0 MPa. This is more than the minimum pressure needed to break the surface of the floor, so it will be damaged.

Questions

P1.49 Write down an equation that defines pressure.

P1.50 What is the SI unit of pressure?

P1.51 Which exerts a greater pressure, a force of 200 N acting on $1.0\ m^2$, or the same force acting on $2.0\ m^2$?

P1.52 What pressure is exerted by a force of 50 000 N acting on $2.5\ m^2$?

P1.53 A swimming pool has a level, horizontal, bottom. Its dimensions are 25.0 m by 5.0 m. The pressure of the water on the bottom is 15 000 Pa. What total force does the water exert on the bottom of the pool? What is the weight of water?

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REFLECTION

Physics involves a lot of calculations. Presenting your calculations clearly helps you check your work. It also helps you identify any errors.

Look back over your calculations. Which steps are you using?

- Identify which values are given in the question.
- Check that the units are consistent and change them if necessary.
- Write down the equation.
- Substitute values into the equation.
- Rearrange the equation if needed.
- Calculate the answer.
- Give units for the answer.

Can you make your calculation answers clearer? Make a note of what you could improve and refer to this next time you are doing calculations.

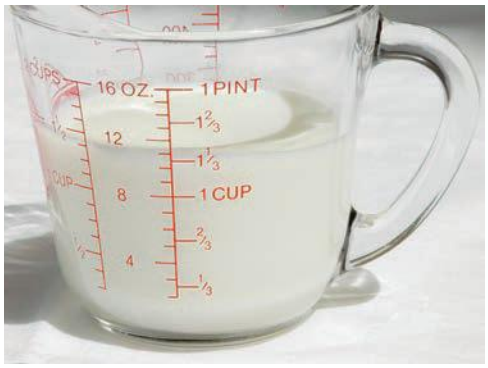
PROJECT P1.01 MAKING MEASUREMENTS

Many subjects in school involve making measurements. Your task is to survey measurements needed in your subjects and identify the measuring instruments which are used. You will then produce a students' guide to measurement. You can present this as a short video, or as a table as shown below.

You should include:

- a range of measuring instruments, including those for measuring length, volume and time
- reference to the units for each of the measurements
- hints on how to ensure the measurements are accurate and precise.

You could extend your project by adding other measurements such as angles or electric current.

Subject	Measurement	Measuring instrument	Picture	Units
food technology	volume of milk	measuring jug		litres or millilitres

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SUMMARY

Length can be measured using a ruler.
Volume can be measured using either calculation or immersion in water.
Density can be calculated using the equation: density = mass ÷ volume.
Taking repeat measurements and calculating an average will give a more precise value.
Speed can be calculated using the equation: average speed = distance ÷ time.
A journey can be described using a distance–time graph or a speed–time graph.
The gradient of a distance–time graph is equal to the speed.
The area under a speed–time graph is equal to the distance travelled.
Acceleration is a change of speed. The gradient of a speed–time graph shows the acceleration.
Acceleration can be calculated as the gradient of a speed–time graph. Or, it can be calculated using the equation: acceleration = change in speed ÷ time.
Velocity is the speed in a particular direction.
Mass is a measure of the amount of matter an object is made up of. Mass is measured in kilograms.
Weight is the gravitational force on an object. Like all forces, weight is measured in newtons.
Forces can change the shape, size or motion of an object.
The resultant force due to two or more forces is the single force which has the same effect as them.
Friction and air resistance are forces which oppose the movement of an object. Friction decreases speed and causes heating.
Forces can cause acceleration. Force, mass and acceleration are related by the equation: force = mass × acceleration.
The moment of a force is a measure of its turning effect.
Moment = force × perpendicular distance from the pivot.
An object is in equilibrium if there are no resultant forces and no resultant moments on it.
The centre of gravity is the point at which the weight of the object appears to act.
An object is more stable if it has a low centre of gravity.
If a force is concentrated on a small area, it will exert more pressure than if the same force was spread over a larger area.
Pressure is the force per unit area and can be calculated using the equation: pressure = force ÷ area. Pressure is measured in pascals.

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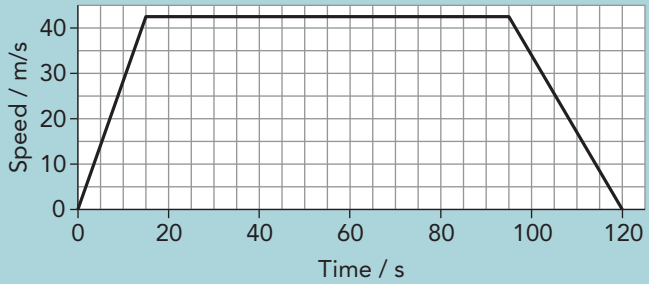
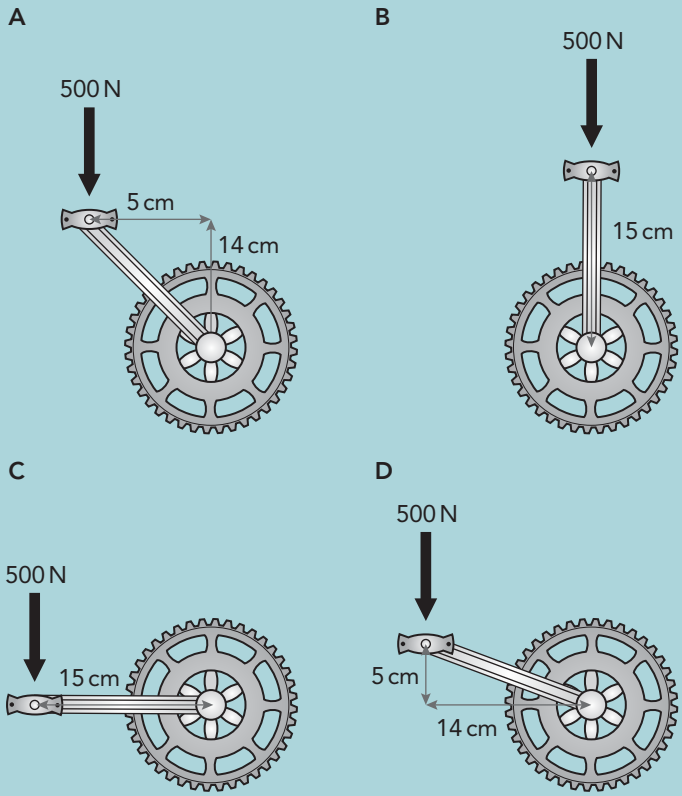
PRACTICE QUESTIONS

1 **Identify** how the distance travelled is shown on this graph.



A the sloping line at the start
B the horizontal part of the line
C the area under the line
D the sloping line at the end **[1]**

2 The pictures show different positions of a bicycle pedal.



Identify the position that would result in the biggest turning force. **[1]**

COMMAND WORD

identify: name/select/recognise.

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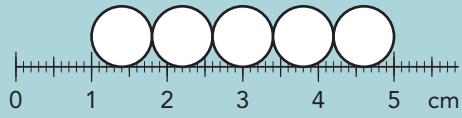
CONTINUED

3 This diagram shows five identical coins lined up against a ruler.



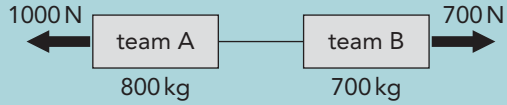
Determine the diameter of each coin. **[1]**

4 This diagram shows the forces during a tug of war competition.

Team A pulls with a force of 1000 N to the left.

Team B pulls with a force of 700 N to the right.

A strong rope joins them.



Determine the size and direction of the resultant force. **[2]**

5 A snail takes part in a snail race. The snail completes the 180 cm course in 7.0 minutes.

Calculate the approximate speed of the snail in m/s. **[1]**

6 **a** Copy and complete this table by calculating the *four* missing values. **[4]**

Object	Mass / g	Volume / cm³	Density / g/cm³
1	160	200	
2	240	20	
3		800	8
4	540		12

b Identify the object, 1–4, that has the greatest mass. **[1]**

c Identify the object, 1–4, that has the greatest volume. **[1]**

d Identify the *two* objects, 1–4, that could be made from the same material. **[1]**

[Total: 7]

COMMAND WORD

determine: establish an answer using the information available.

COMMAND WORD

calculate: work out from given facts, figures or information.

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CONTINUED

7 The table shows Usain Bolt's split times from his world record 100 m run in Berlin in 2009. Each split time is for a 10 m section of the 100 m distance. The time for the first 10 m includes his reaction time of 0.146 s before he left his blocks.

Section / m	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	90–100
Time / s	1.89	0.99	0.90	0.86	0.83	0.82	0.81	0.82	0.83	0.83

a Calculate the time that Usain Bolt takes to run the first 10 metres from the moment he starts moving. **[1]**

b Calculate Usain Bolt's average speed over the first 10 metres from the moment he starts moving. **[1]**

c Calculate Usain Bolt's maximum speed over the first 10 metres. Ignore his reaction time and assume his acceleration is constant. **[1]**

d Calculate Usain Bolt's acceleration over the first 10 metres. Ignore his reaction time and assume his acceleration is constant. **[1]**

e Calculate Usain Bolt's top speed in the race. Show your working. **[1]**

[Total: 5]

8 **State** *two* ways that a turning force can be increased. **[2]**

9 State the *two* conditions for a body to be in equilibrium. **[2]**

10 An elephant has a mass of 5000 kg. The area of an elephant's foot is 0.13 m^2.

A woman has a mass of 60 kg. The area of her stiletto heel is 25 mm^2.

a State the equation linking weight, mass and *g*. Use the equation to calculate the weights of the elephant and the woman. **[3]**

b State the equation that links (solid) pressure, force and area. **[1]**

c Calculate the pressures exerted by the elephant and the woman. **[2]**

d Use the pressure values you calculated to **suggest** why the woman might cause more damage to a floor than an elephant. **[1]**

[Total: 7]

TIP

Remember that weight is a force and that you need to convert the area of the stiletto heel into m^2.

COMMAND WORDS

state: express in clear terms.

suggest: apply knowledge and understanding to situations where there is a range of valid responses in order to make proposals/put forward considerations.

SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
measure length, volume and time	P1.01			
calculate the volume of a cuboid from measurements made with a ruler	P1.01			
calculate density	P1.02			

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CONTINUED

I can	See topic . . .	Needs more work	Almost there	Confident to move on
perform experiments to determine the density of a liquid and a regular shaped solid	P1.02			
perform an experiment to determine the density of an irregular shaped solid	P1.02			
determine lengths and times precisely by repeated measurement and calculation of a mean value	P1.03			
calculate speed	P1.04			
plot a distance–time graph to illustrate a journey	P1.04			
plot a speed–time graph to illustrate a journey	P1.05			
work out speed from a distance–time graph	P1.05			
work out the distance travelled from a speed–time graph	P1.05			
identify where an object is accelerating from a speed–time graph	P1.05			
calculate acceleration from a speed–time graph	P1.05			
calculate acceleration using the equation: acceleration = change in speed ÷ time	P1.05			
state how velocity is different from speed	P1.05			
define mass and state the unit of mass	P1.06			
define weight and state the unit of weight	P1.06			
recall four ways that a force can affect an object	P1.07			
calculate the resultant force due to two or more forces acting along the same line	P1.07			
describe how friction affects the speed and temperature of a moving object	P1.07			
recall and use the equation which relates force, mass and acceleration	P1.08			
describe an experiment to investigate the stretching of a loaded spring, and explain the results	P1.09			
give everyday examples of a turning force	P1.10			
understand that increasing the size of a force or its distance from the pivot increases its turning effect	P1.10			

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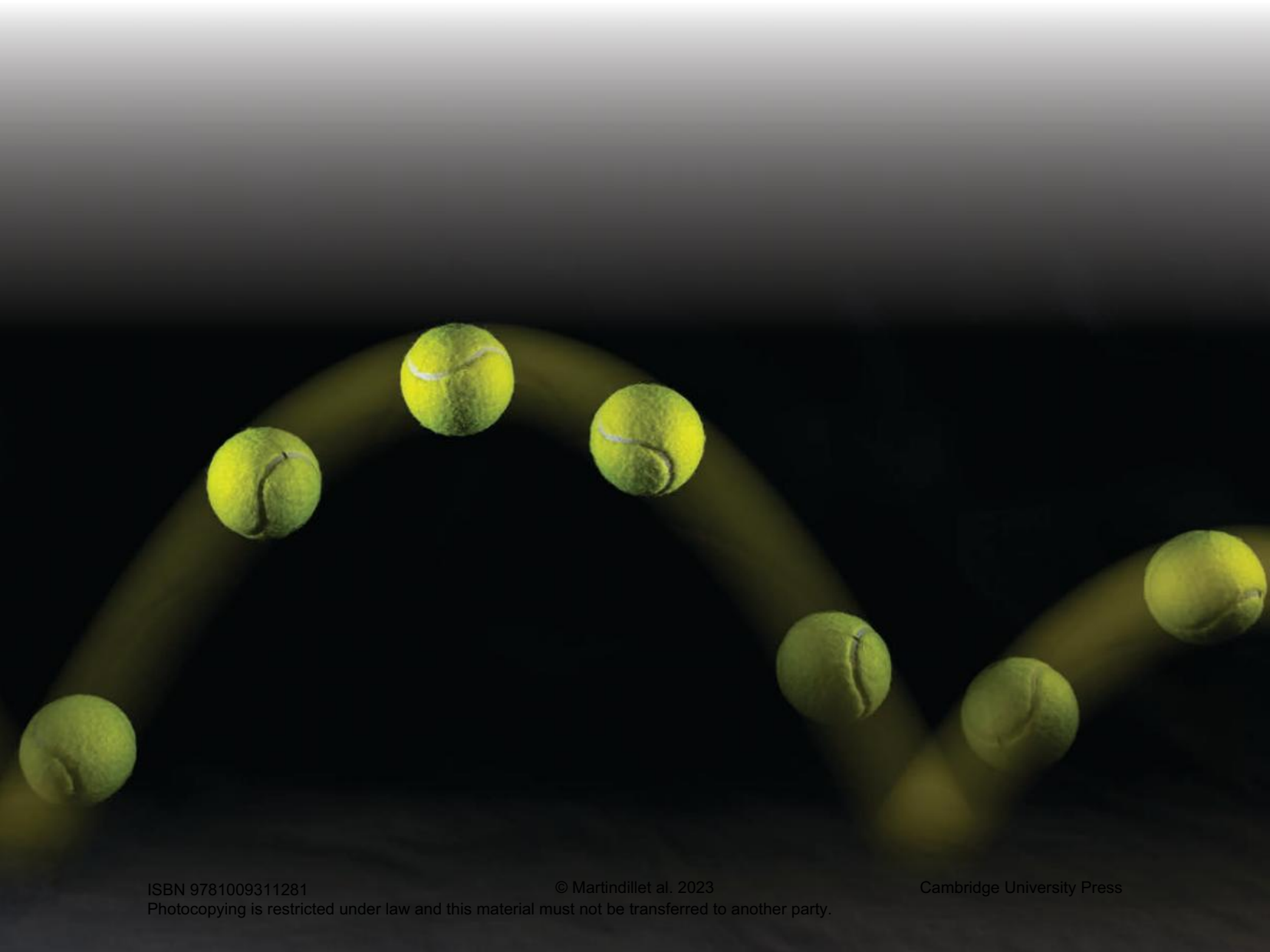
CONTINUED

I can	See topic . . .	Needs more work	Almost there	Confident to move on
recall and use the equation: moment = force × perpendicular distance from the pivot	P1.10			
state the conditions for an object to be in equilibrium	P1.10			
apply the principle of moments to different situations	P1.10			
describe an experiment to find the centre of gravity of a piece of card	P1.10			
describe how the location of the centre of gravity of an object affects its stability	P1.10			
recall and use the equation which relates pressure, force and area.	P1.11			



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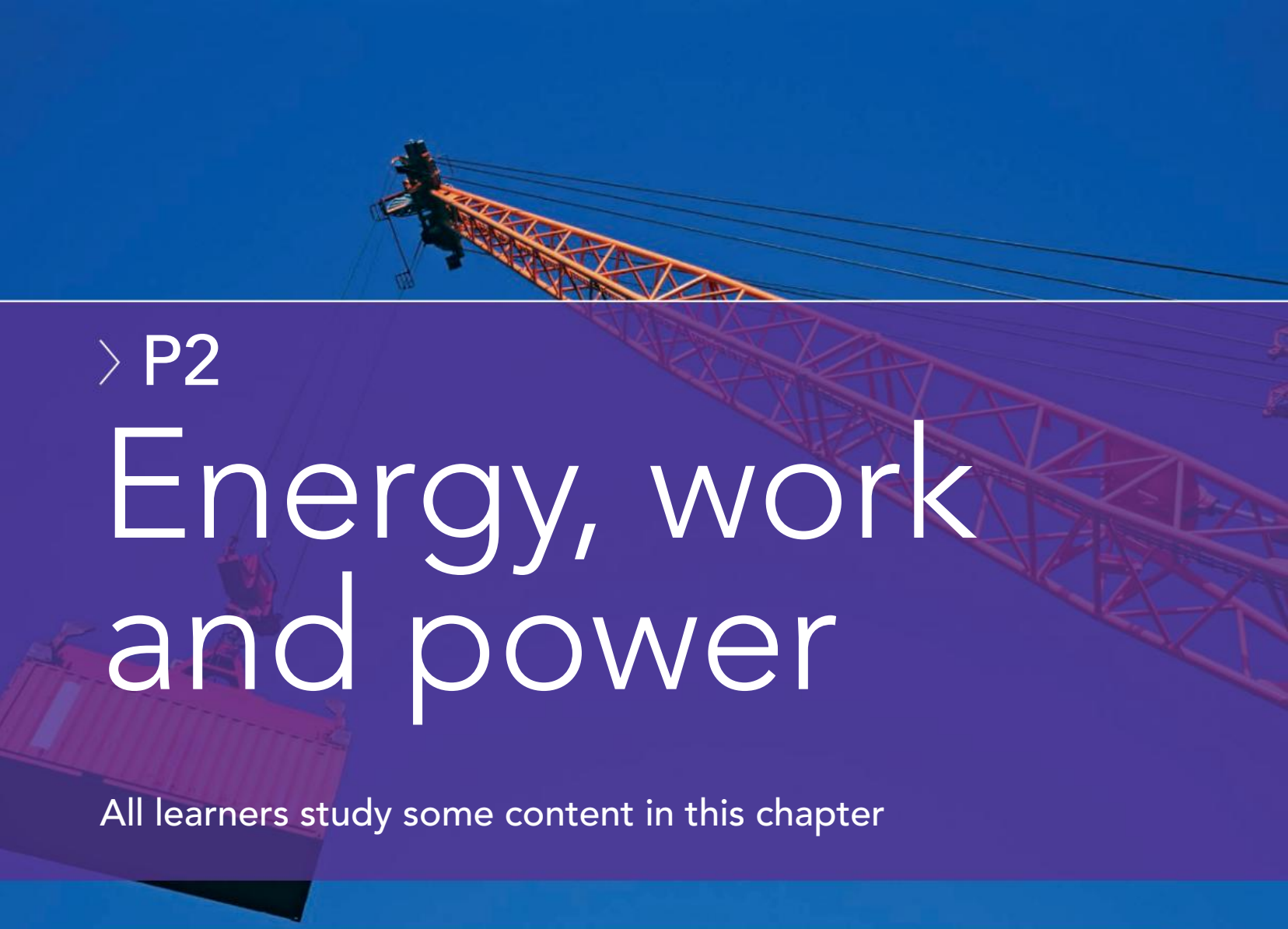

P2

Energy, work and power

All learners study some content in this chapter

IN THIS CHAPTER YOU WILL:

- identify changes in different energy stores
- recognise different energy transfers
- understand the meaning of energy efficiency
- calculate efficiency
- apply the principle of conservation of energy
- calculate potential energy and kinetic energy
- distinguish between renewable and non-renewable energy sources
- describe how electricity or other useful stores of energy may be obtained from different energy resources
- consider the advantages and disadvantages of each energy resource
- understand that the Sun is the source of energy for all our energy resources except geothermal, nuclear and tidal
- understand that energy is released by nuclear fusion in the Sun
- understand that work is done when a force causes movement
- relate power to work done and time taken
- use the equation $W = Fd = \Delta E$ to calculate work done
- use the equations $P = \frac{\Delta E}{t}$ and $P = \frac{W}{t}$ to calculate power.

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BEFORE YOU START

Work with a classmate to describe the **energy** transfers that are taking place in each diagram of Figure P2.01.

What do you already know about energy?

With a classmate, draw an energy mind map to include everything you know about this topic, including the principle of conservation of energy.

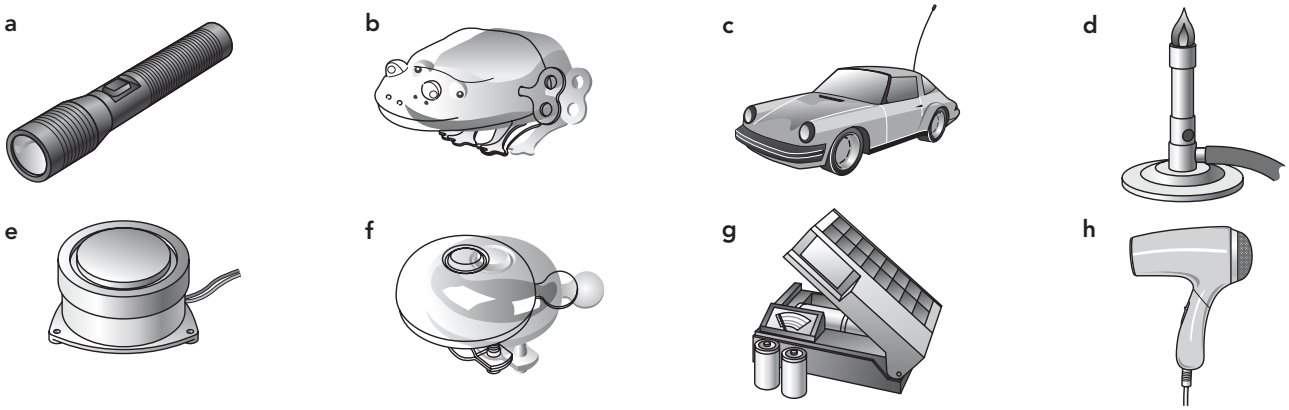

Figure P2.01 a: Flashlight switched on. **b:** Wound up toy. **c:** Moving radio-controlled car. **d:** Bunsen burner. **e:** Loudspeaker in use. **f:** Ringing bicycle bell. **g:** Solar-powered battery. **h:** Hair dryer in use.

KEY WORD

energy: quantity that must be changed or transferred to make something happen.

SCIENCE IN CONTEXT P2.01

Is thorium the perfect fuel?

Kirk Sorensen worked for NASA to come up with a reliable source of energy for a Moon base. None of the energy resources that are used on Earth were suitable. But then he found a book about liquid fluoride thorium reactors (or 'lifters'), an environmentally friendly and safe version of nuclear power (Figure P2.02). They were being developed by the USA so that aircraft carrying nuclear bombs would only have to land to change crews and take on supplies. But the experiment was abandoned in 1956 because missiles could more easily send nuclear bombs over great distances.

Nuclear power stations need water, but a lifter would not. This would make it suitable for the Moon. But Sorenson thought, 'Why not have them here on Earth?' There are huge reserves of thorium fuel available, they produce tiny amounts of radioactive waste, an accidental meltdown would be impossible, and it would be extremely difficult to make a nuclear bomb using a lifter.

Figure P2.02: Pellets of thorium.

Discussion questions

1 Explain why energy resources used on Earth would not be suitable for the Moon.

2 Would you be in favour of nuclear power based on a lifter? Explain your answer.

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P2.01 Energy stores, transfers and conservation

Energy is hard to define. It is easier to describe it using examples. Energy is the quantity which is transferred whenever we observe a change, such as a change of motion or temperature, a lamp shining or a power station producing electricity.

Energy is measured in **joules**.

Energy stores

Energy can be stored in many different ways. Table P2.01 shows some of the main energy stores. Many situations involve lots of different stores of energy as shown in Figure P2.03.

Store	Examples
Kinetic energy	Cars, moving water, runners.
Gravitational potential energy	Aeroplanes, divers.
Chemical energy	Food, fuel, batteries.
Elastic (strain) energy	Catapults, stretched elastic bands.
Nuclear energy	Nuclear power stations, the Sun.
Electrostatic energy	Thunderclouds.
Internal (thermal) energy	Hot water, human bodies.

Table P2.01: The different ways energy can be stored.

Figure P2.03: This car driving uphill has several stores of energy: kinetic as it is moving, gravitational potential as it has driven uphill, chemical in its fuel tank and internal as the engine will have heated up.

KEY WORDS

joule: the SI unit for energy transferred or work done.

kinetic energy: the energy store of a moving object.

gravitational potential energy: the energy store of an object raised up against the force of gravity; more generally, it is the distance between particles or bodies.

chemical energy: energy stored in bonds between atoms that can be released when chemical reactions take place.

elastic (strain) energy: energy stored in the changed shape of an object.

nuclear energy: energy stored in the nucleus of an atom.

electrostatic energy: the energy stored when charges are separated or squashed together.

internal (thermal) energy: the energy of an object; the total kinetic and potential energies of its particles.

Questions

P2.01 What name is given to the energy of a moving object?

P2.02 How can the gravitational potential energy of an object be increased?

P2.03 What energy is stored in a stretched spring?

P2.04 Give examples of objects or materials which store:

- **a** kinetic energy
- **b** gravitational potential energy
- **c** elastic energy
- **d** internal energy.

Energy transfers

Energy stores are potential energy. This is energy which is available but is not being used. Energy can also transfer between stores, but the total amount of energy never changes. So, energy can be stored or it can be transferred in an **event** or a **process** (Table P2.02).

KEY WORDS

event: something that happens or takes place, often at a specific time and place.

process: a series of actions or steps, often taking place over a long period of time.

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Energy transfers	Example events and processes
Forces (mechanical work)	Kicking a football increases its store of kinetic energy causing it to move. When a force makes something move, we say it is **doing work**.
Electrical currents	An electrical current transfers energy from the chemical energy store of a flashlight battery to the internal energy of a bulb.
Heating	Heating water with a Bunsen burner flame transfers energy from the chemical store of the gas to the internal energy store of the water.
Waves	Infrared (heat) radiation from the Sun is transferred through space by waves and can be used to increase the thermal energy store of water in a **solar panel**.

Table P2.02: Energy can be transferred between stores.

KEY WORDS

doing work: transferring energy by means of a force.

solar panel: used to collect energy that is transferred by light from the Sun.

Energy can be transferred from one store to another, even within the same object.

For example, when you climb a hill, you are transferring energy from your chemical store to your gravitational potential energy store. Figures P2.04 and P2.05 illustrate some energy transfers. At a major rock concert, giant loudspeakers transfer sound to the audience. Extra generators may have to be brought on to the site to act as a source of energy to power the speaker systems. Much of the energy supplied is wasted as thermal energy, because only a fraction of the energy is transferred by sound.

Figure P2.04: Light and sound energy make this concert impressive.

When a catapult fires a ball, energy is transferred from the elastic store of the catapult to the kinetic store of the ball. If the ball is fired vertically upwards, energy from the kinetic energy store is transferred to the gravitational potential energy store, until there is nothing left in the kinetic energy store. The ball stops moving upwards and starts falling. Now, energy is transferred from the gravitational store back to the kinetic store.

Figure P2.05: When the boy lets go, the store of elastic energy is transferred to the ball's store of kinetic energy.

Questions

P2.05 Look at the physical clues in the left column of Table P2.03. For each, write down which energy store is changing.

Physical clue	Which energy store is changing?
material changing shape	
object changing speed	
chemical reaction	
change of temperature	
nuclear fission or fusion	

Table P2.03: Changing energy stores.

P2.06 What energy transfers are going on in the following?

a Coal is burnt to heat a room and to provide a supply of hot water.

b A student uses an electric lamp while she is doing her homework.

c A hair dryer is connected to the mains electricity supply. It blows hot air at the user's wet hair. It whirrs as it does so.

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ACTIVITY P2.01

Energy changes

Examine some devices that transfer energy. Some ideas are shown in Figure P2.01 in the 'Before you start' box.

- In pairs, examine each of the devices you are provided with. For each of them, describe what energy transfers are going on in the device.
- With your partner, decide how to record and present the energy transfers you have described for each device.
- Compare your answers with the answers of other members of the class and correct or add to your own answers.

Conservation of energy

When energy is transferred from one store to another, it is often the case that some of the energy ends up as unwanted energy. For example, a light bulb transfers light (which we want) and heat (which is not wanted).

This is an example of a very important idea: the **principle of conservation of energy**:

> In any energy transfer, the total amount of energy before and after the transfer is constant.

This tells us something very important about energy: it cannot be created or destroyed. The total amount of energy is constant. If we measure or calculate the amount of energy before a transfer, and again afterwards, we will always get the same result. If we find any difference, we must look for places where energy may be entering or escaping unnoticed.

KEY WORDS

principle of conservation of energy: energy cannot be created or destroyed; it can only be stored or transferred.

WORKED EXAMPLE P2.01

A car burns 3×10^5 J of fuel (chemical energy) per second. It has 1.3×10^5 J of kinetic energy and gains 0.7×10^5 J of gravitational potential energy as it goes up a slope. How much energy transfers away from the car through thermal energy transfer?

Step 1: Write down what you know, and what you want to know.

input energy:

chemical energy = 3×10^5 J

output energy:

kinetic energy = 1.3×10^5 J

gravitational potential energy = 0.7×10^5 J

thermal energy transferred = ?

Step 2: Write down any equations or useful principles.

According to the principle of conservation of energy, the total input energy should equal the total output energy.

Step 3: Apply the principle to this problem and substitute known values to solve the problem.

input energy = output energy

chemical energy = kinetic energy + gravitational potential energy + thermal energy

3×10^5 J = 1.3×10^5 J + 0.7×10^5 J + thermal energy

= 1.0×10^5 J transfers away from the car through thermal energy transfer.

Answer

1.0×10^5 J transfers away from the car as thermal energy.

Question

P2.07 A light bulb is supplied with 60 J of energy each second.

a How many joules of energy are transferred from the bulb each second?

b 4 J of energy are transferred from the lamp each second as light. How many joules of energy are transferred each second by heating?

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Energy efficiency

Most wasted energy is transferred away as heat. There are two main reasons for this.

When fuels are burnt (perhaps to generate electricity, or to drive a car), heat is produced. The desired energy change is from chemical to electrical or kinetic, but some is always wasted as thermal energy.

Friction is often a problem when things are moving. **Lubrication** can help to reduce friction. A streamlined car design can reduce air resistance. But it is impossible to eliminate (remove) friction entirely from machines with moving parts. Friction generates heat.

Another common wasted energy transfer is sound. Noisy machinery, loud car engines and so on, all transfer sound to the atmosphere. However, even loud noises contain very little energy, so there is little to be gained (in terms of energy) by reducing noise.

It is important to make good use of the energy resources available to us. This is because energy is expensive, supplies are often limited, and our use of energy can damage the environment. Energy transfers wherein little energy is wasted and most of the energy is transferred in a useful way are said to be efficient.

Be careful, the word '**efficiency**' is used in everyday life, but often it is used to mean quickly, which is not the same as the scientific meaning.

Table P2.04 shows the typical efficiencies for some important devices. You can see that even the most modern gas-fired power station is only 50% efficient. Half of the energy it is supplied with is wasted.

Device	Typical efficiency
electric heater	100%
large electric motor	90%
washing machine motor	70%
gas-fired power station	50%
diesel engine	40%
car petrol engine	30%
steam locomotive	10%

Table P2.04: Energy efficiencies. Most devices are less than 100% efficient because they produce waste heat. An electric heater is 100% efficient because all of the electrical energy supplied is transferred to thermal energy. There is no problem with waste here.

KEY WORDS

lubrication: usually a liquid, it allows two surfaces to slide past each other more easily.

efficiency: the fraction (or percentage) of energy supplied that is usefully transferred.

Efficiency is important because we pay for the energy we use even if it is wasted. The light bulbs in Figure P2.06 both produce the same amount of light, but bulb A has an efficiency of only 10%. This means 90% of the electrical energy it uses is wasted as heat. The homeowner is paying for this. Bulb B is much more efficient – around 85% – so much less energy (and money) is wasted.

Bulb **a** has to be supplied with much more energy than bulb **b**. As much of our electricity comes from power stations which burn fossil fuels, this means using bulb **a** burns more fossil fuel and so contributes more to global warming than bulb **b**.

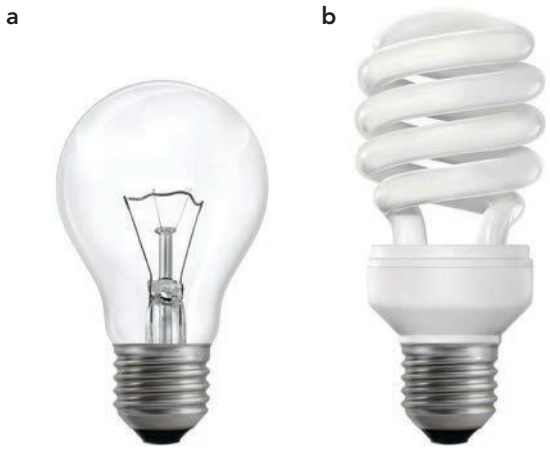

Figure P2.06: Bulb **a** produces a lot of heat and so is not efficient. The more modern bulb **b** wastes very little energy as heat.

Questions

P2.08 **a** In what way is energy usually wasted?

b Name another way in which energy is often wasted.

P2.09 Give *three* reasons why it is important not to waste energy.

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Calculating efficiency

You can see from Table P2.04 that efficiency is often given as a percentage. We can calculate the efficiency and percentage efficiency of an energy change as follows:

KEY EQUATIONS

$$\text{efficiency} = \frac{\text{useful energy output}}{\text{total energy input}}$$

$$\text{percentage efficiency} = \frac{\text{useful energy output}}{\text{total energy input}} \times 100\%$$

Efficiency is expressed as a number (no units) up to a value of 1. This number can be multiplied by 100 to get percentage efficiency. Percentage efficiency greater than 100% is impossible.

When the filament lamp from Figure P2.06 is supplied with 100 J of energy, it produces 15 J of useful light. The efficiency of the lamp can be calculated using either of these equations.

Questions

P2.10 Calculate the efficiency of the energy-efficient lamp which uses 25 J of electrical energy and produces 15 J of light.

P2.11 A tidal power station is expected to produce 32 TJ of energy (1 TJ = 10^{12} J) when the tides provide it with 100 TJ of gravitational potential energy. What is the efficiency of the power station?

P2.12 A tungsten-filament lamp is 4% efficient. How much electrical energy must be supplied to the lamp each second when it produces 6 J of light per second?

P2.02 Energy calculations

Energy is not simply an idea. It is also a quantity that we can calculate.

Gravitational potential energy

Mountaineering on the Moon should be easy (see Figure P2.07). The Moon's gravity is much weaker than the Earth's, because the Moon's mass is only one-eightieth of the Earth's. This means that the weight of an astronaut on the Moon is a fraction of his or her weight on the Earth. In principle, it is possible to jump higher on the Moon than on the Earth.

Earlier, we saw that an object's gravitational potential energy depends on its height above the ground. The higher it is, the greater its gravitational potential energy. If you lift an object upwards, you provide the force needed to increase its gravitational potential energy. The heavier the object, the greater the force needed to lift it, and hence the greater its gravitational potential energy.

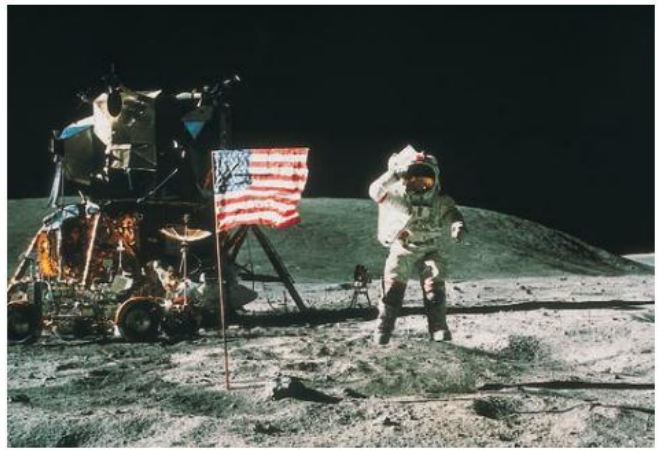

Figure P2.07: Astronauts on the Moon. The gravitational field strength on the surface of the Moon is one-sixth of what it is on Earth. Experiments on the Moon have shown that a golf ball can be hit much further than on Earth. This is because it travels a much greater distance horizontally before gravity pulls it back to the ground.

This suggests that an object's gravitational potential energy depends on two factors:

- the object's weight, *mg*: the greater its weight, the greater its gravitational potential energy
- the object's height, *h*, above ground level: the greater its height, the greater its gravitational potential energy.

This is illustrated in Figure P2.08. From the numbers in the diagram, you can see that a change in gravitational potential energy is simply calculated by multiplying weight by height

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(assuming that an object's gravitational potential energy is zero when it is at ground level). We can write this as an equation for gravitational potential energy.

KEY EQUATION

change in gravitational potential energy = weight × change in height

$$\Delta E_p = mg\Delta h$$

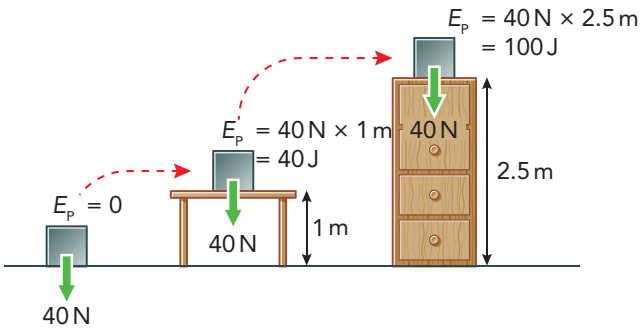

Figure P2.08: The gravitational potential energy of an object increases as it is lifted higher. The greater its weight, the greater its gravitational potential energy.

WORKED EXAMPLE P2.02

An athlete of mass 50 kg runs up a hill. The foot of the hill is 400 metres above sea-level. The summit is 1200 metres above sea-level. By how much does the athlete's gravitational potential energy increase? Assume that gravitational field strength g = 10 N/kg.

Step 1: Assume that gravitational potential energy is zero at the foot of the hill. Calculate the increase in height.

Δh = 1200 m – 400 m = 800 m

Step 2: Write down the equation for gravitational potential energy, substitute values and solve.

ΔE_p = weight × change in height
= $mg\Delta h$
= 50 kg × 10 N/kg × 800 m
= 400 000 J
= 400 kJ

Answer

The athlete's gravitational potential energy increases by 400 kJ.

Kinetic energy

It takes energy to make things move. You transfer energy to a ball when you throw it or hit it. A car uses energy from its fuel to get it moving. Elastic energy stored in a stretched piece of rubber is needed to fire a pellet from a catapult. So a moving object is a store of energy. This energy is known as kinetic energy.

We often make use of an object's kinetic energy. To do this, we must slow it down. For example, moving air turns a wind turbine. This slows down the air, reducing its kinetic energy. The energy extracted can be used to turn a generator to produce electricity.

This suggests that the kinetic energy of an object depends on two factors:

- the object's mass *m*: the greater the mass, the greater its kinetic energy
- the object's speed *v*: the greater the speed, the greater its kinetic energy.

These are combined in an equation for kinetic energy:

KEY EQUATION

$$\text{kinetic energy} = \frac{1}{2} \times \text{mass} \times \text{speed}^2$$

$$E_K = \frac{1}{2}mv^2$$

Worked example P2.03 shows how to use the equation to calculate the kinetic energy of a moving object.

WORKED EXAMPLE P2.03

A van of mass 2000 kg is travelling at 10 m/s.

a Calculate its kinetic energy.

b Its speed increases to 20 m/s. By how much does its kinetic energy increase?

Step 1: Calculate the van's kinetic energy at 10 m/s.

$$E_K = \frac{1}{2}mv^2$$
$$= \frac{1}{2} \times 2000\,\text{kg} \times (10\,\text{m/s})^2$$
$$= 100\,000\,\text{J}$$
$$= 100\,\text{kJ}$$

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P2.03 CONTINUED

Step 2: Calculate the van's kinetic energy at 20 m/s.

$$E_K = \frac{1}{2}mv^2$$
$$= \frac{1}{2} \times 2000\,\text{kg} \times (20\,\text{m/s})^2$$
$$= 400\,000\,\text{J}$$
$$= 400\,\text{kJ}$$

Step 3: Calculate the change in the van's kinetic energy.

change in kinetic energy = 400 kJ − 100 kJ
= 300 kJ

Answer

a The van's kinetic energy when travelling at 10 m/s is 100 kJ.

b The van's kinetic energy increases by 300 kJ when it speeds up from 10 m/s to 20 m/s.

When the van starts moving from rest and speeds up to 10 m/s, its kinetic energy increases from 0 to 100 kJ. When its speed increases by the same amount again, from 10 m/s to 20 m/s, its kinetic energy increases by 300 kJ, three times as much. It takes a lot more energy to increase your speed when you are already moving quickly. That is why a car's fuel consumption starts to increase rapidly when the driver tries to accelerate in the fast lane of a motorway.

It is worth looking at Worked example P2.03 in detail, since it illustrates several important points.

When calculating kinetic energy using $E_k = \frac{1}{2}mv^2$, take care!

Only the speed is squared. Using a calculator, start by squaring the speed. Then multiply by the mass, and finally divide by two.

When the van's speed doubles from 10 m/s to 20 m/s, its kinetic energy increases from 100 kJ to 400 kJ. In other words, when its speed increases by a factor of two, its kinetic energy increases by a factor of four. This is because kinetic energy depends on speed squared. If the speed trebled (increased by a factor of three), the kinetic energy would increase by a factor of nine (see Figure P2.09). This helps to explain why a small increase in a car's speed makes a collision much more dangerous, as the energy of the car is linked to the damage it will do.

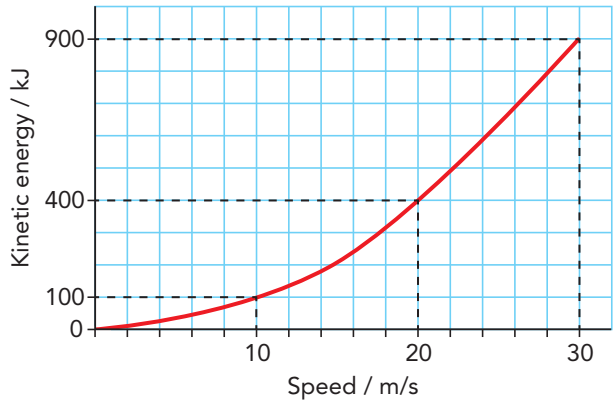

Figure P2.09: The faster the van travels, the greater its kinetic energy. The graph shows that kinetic energy increases more and more rapidly as the van's speed increases.

Questions

P2.13 In the following examples, is the object's gravitational potential energy increasing, decreasing or remaining constant?

a A balloon rises in the air.

b A bird flies at a constant height on its migration route.

c A raindrop falls from the sky.

P2.14 It is claimed that Superman can jump 200 metres vertically upwards. If he has a mass of 100 kg, by how much does his gravitational potential energy increase?

P2.15 Usain Bolt has a mass of 86 kg. When he runs at 12 m/s, what is his kinetic energy?

P2.16 How much kinetic energy is stored by a bullet with a mass of 10.5 g travelling at 553 m/s?

P2.17 Which has more kinetic energy, a 2.0 g bee flying at 1.0 m/s, or a 1.0 g wasp flying at 2.0 m/s?

P2.03 Energy resources

Here on Earth, we rely on the Sun for most of the energy we use. The Sun is a fairly average star, 150 million kilometres away. The heat and light we receive from it take about eight minutes to travel through empty space to get here. Plants absorb this energy in the process of photosynthesis, and animals are kept warm by it.

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Most of the energy we use comes from the Sun, but only a small amount is used directly from the Sun. On a cold but sunny morning, you might sit in the sunshine to warm your body. Your house might be designed to collect warmth from the Sun's rays, perhaps by having larger windows on the sunny side. However, most of the energy we use comes only indirectly from the Sun. It must be transferred in a more useful form, such as electricity.

Figure P2.10 shows the different resources that contribute to the world's energy supplies. This chart reflects patterns of energy consumption in 2018. Many people today live in industrialised countries and consume large amounts of energy, particularly from fossil fuels (coal, oil and gas). People living in less-developed countries consume far less energy, which they get mostly from biofuels, particularly wood. We will now look at these groups of fuels in turn, in addition to other energy resources.

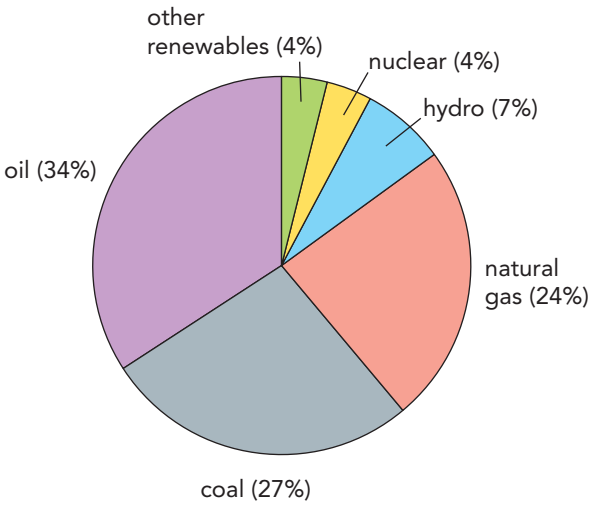

Figure P2.10: World energy use, by resource. This chart shows people's energy consumption of different resources across the world in 2018. Around 85% of all energy comes from fossil fuels.

Renewables and non-renewables

Figure P2.10 shows that most of the energy supplies we use are fossil fuels: coal, oil and gas. The Earth's supplies of these are rapidly being used up. They are described as **non-renewables**. Once used, they are gone forever. Burning fossil fuels also causes global warming.

Other sources of energy, such as wind, solar and biofuel, are described as **renewables**. This is because, when we use them, they will soon be replaced. The wind will blow again, the Sun will shine again. After harvesting a biofuel crop, we can grow another crop.

Energy direct from the Sun

We can generate electricity directly from sunlight. The Sun's rays shine on a large array of **solar cells** (also known as **photocells** or **photovoltaic cells**). The solar cells absorb the energy of the rays, and electricity is produced. Solar cells are used on roofs and in large arrays such as that shown in Figure P2.11.

Figure P2.11: An array of solar cells inside the Vansad National Park, India.

KEY WORDS

non-renewables: an energy resource that is gone forever once it has been used.

renewables: an energy resource that will be replenished (replaced) naturally when used.

solar cell/photocell/photovoltaic cell: an electrical device that transfers the energy of sunlight directly to electricity, by producing a voltage when light falls on it.

Wind power

Wind is caused by the effects of the Sun. The Sun heats some parts of the atmosphere more than others. Heated air expands and starts to move around – this is a convection current. This is the origin of winds. There are many technologies for extracting energy from the wind. Wind turbines can generate electricity (see Figure P2.12).

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Figure P2.12: These giant turbines are part of a wind farm at Xinjiang in China. They produce as much electricity as a medium-sized coal-fired power station.

Wave power

Most of the energy of winds is transferred to the sea as waves, which are formed by friction between the wind and the water. The kinetic energy of the waves can turn a turbine to generate electricity.

Hydroelectric power

One of the smallest contributions to the chart in Figure P2.10 is hydroelectric power. This is produced in hydroelectric power stations (see Figure P2.13). Water stored behind a dam is released to turn turbines, which make generators spin.

Figure P2.13: The giant Itaipú dam on the Paraná River in South America generates electricity for Brazil and Paraguay.

Biofuels

For many people in the world, wood is the most important fuel. It warms their homes and provides the heat necessary for cooking their food. Wood is made by trees and shrubs. It stores energy that the plant has captured from sunlight in the process of photosynthesis. When we burn wood, we are releasing energy that came from the Sun in the recent past, perhaps ten or a hundred years ago.

Wood is just one example of a **biofuel**. Others include animal dung (Figure P2.14) and biogas, generated by rotting vegetable matter.

Figure P2.14: A Maasai blowing into elephant dung to make fire in a village in West Kilimanjaro, Tanzania.

Fossil fuels

Oil, coal and gas are all examples of **fossil fuels**. These are usually hydrocarbons (compounds of hydrogen and carbon). When they are burnt, they combine with oxygen from the air and energy is released as heat.

We can think of a fossil fuel as a store of chemical energy. Fossil fuels can be burnt in power stations to generate electricity (see Figure P2.15).

KEY WORDS

biofuel: material, recently living, used as a fuel.

fossil fuels: material, formed from long-dead material, used as a fuel.

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Figure P2.15: Coal is a fossil fuel. A fossil is any living material that has been preserved for a long time. Usually, its chemical composition changes during the process. Coal sometimes shows evidence of the plant material from which it formed. Sometimes you can see fossilised creatures that lived in the swamps of the Carboniferous era. These creatures died along with the trees that eventually became coal.

Nuclear fuels

Nuclear power was developed in the second half of the 20th century. It is a very demanding technology, which requires very strict controls, because of the serious damage that can be caused by an accident at a nuclear power station.

The fuel for a nuclear power station (Figure P2.16) is usually uranium, sometimes plutonium. These are radioactive materials. Inside a nuclear reactor, the radioactive decay of these materials is speeded up so that the energy they store is released much more quickly. This is the process of **nuclear fission**.

Figure P2.16: Belleville nuclear power station in France.

Geothermal energy

The interior of the Earth is hot. People make use of this **geothermal energy** where hot rocks are found at a shallow depth below the Earth's surface. These rocks are hot because of the presence of radioactive substances inside the Earth. To make use of this energy, water is pumped down into the rocks, where it boils. High-pressure steam returns to the surface, where it can be used to generate electricity.

KEY WORDS

nuclear fission: the process by which energy is released from nuclear fuels by the splitting of a large heavy nucleus into two or more smaller nuclei.

geothermal energy: energy stored in hot rocks underground.

Tidal energy

A tidal power station is similar to a hydroelectric power station: electrical power is generated by moving water. A barrage (dam) is built across a river estuary (where a river meets the sea) creating a reservoir. As the tide goes in and out, water passes through turbines in the dam.

Questions

P2.18 Name an energy resource which is renewable.

P2.19 Name an energy resource which is *not* renewable.

P2.20 Explain why wind and solar energy are described as renewable energy resources.

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P2.21 What form of energy is stored in fossil fuels and biofuels?

P2.22 What is the difference between biofuels and fossil fuels?

P2.23 Name *two* energy resources which involve radioactive materials.

Using energy resources to generate electricity

Many of the energy resources in this chapter produce electricity so that it can be transferred to where it is needed. The thermal energy produced when fossil fuels are burnt (Figure P2.17) or when nuclear fission takes place is used to heat water in a **boiler** to form steam. The steam turns the blades of a **turbine**, transferring thermal energy into kinetic energy. The turbine is linked by an axle to a **generator** where a voltage is induced in conducting wires when they move in a magnetic field.

The details of how thermal energy is produced in power stations that use fuel will vary, but they will all have a boiler, turbine and generator.

Those energy resources that do not use a fuel, such as wind, waves and tides, will not need a boiler, but they will still use a turbine linked to a generator to produce electricity. Moving air and moving water can turn a turbine directly (see Figure P2.18).

Figure P2.18: A wind turbine being constructed. The turbine blades will be turned by the wind and will turn the generator to produce electricity.

KEY WORDS

boiler: device where thermal energy is transferred to water to turn it into steam.

turbine: a device that is made to turn by moving air, steam or water; often used to generate electricity.

generator: a device which generates electricity using electromagnetic induction.

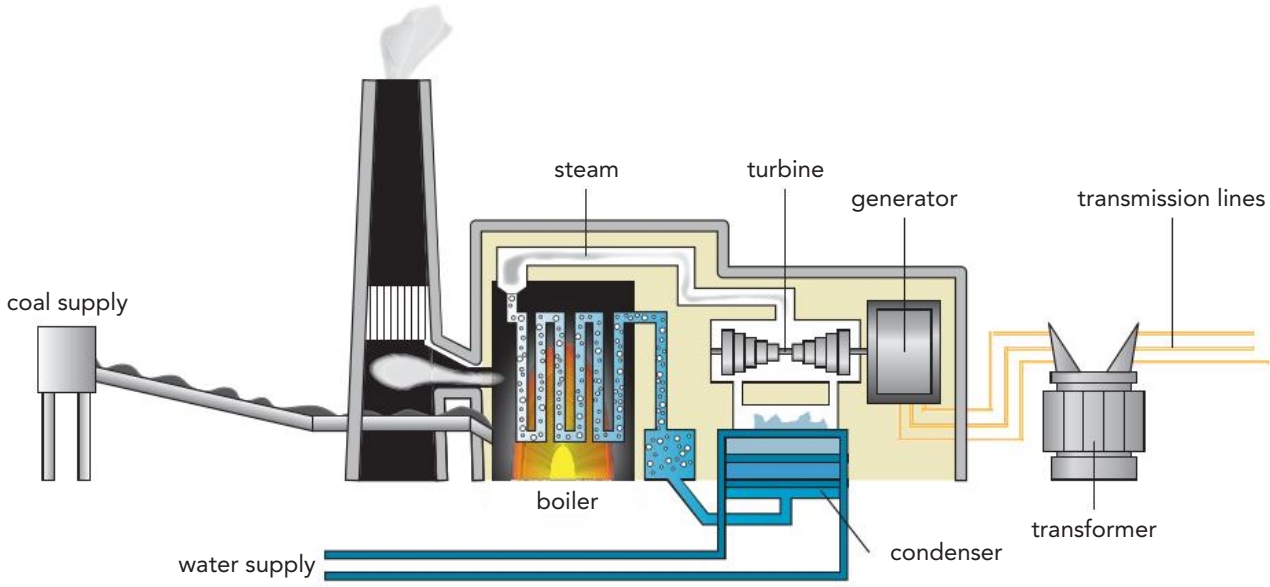

Figure P2.17: A schematic of a coal-fired power station.

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Comparing energy resources

We use fossil fuels a lot because they represent concentrated sources of energy. A modern gas-fired power station might occupy the space of a football ground and supply a town of 100 000 people. To replace it with a wind farm might require 50 or more wind turbines spread over an area of several square kilometres. The wind is a much more dilute source of energy.

This illustrates some of the ideas that we use when comparing different energy resources. Each has its advantages and disadvantages. We need to think about the following factors.

Renewability

As we have seen, there are limited reserves of fossil fuels. The same applies to uranium nuclear fuel. However, there are plentiful reserves of alternative nuclear fuels such as thorium. All other energy resources are renewable, including all those that can be traced back to radiation from the Sun. The most important advantage of renewable resources is that, once installed, they do not contribute to global warming.

Cost

We should separate initial costs from running costs. A solar cell is expensive to buy but there are no costs for fuels – sunlight is free! While nuclear fuel is cheap, the costs of decommissioning nuclear power plants are high.

Availability

France uses nuclear power to produce about 75% of its electricity because it has few alternative energy resources. Norway has plenty of rainfall and mountains so generates about 95% of its electricity from hydroelectric power. Iceland uses geothermal energy, which is quite localised.

Reliability

Is the energy supply constantly available? The wind is variable, so wind power is unreliable. Wars and trade disputes can interrupt fuel supplies.

Scale

A fossil fuel power station can be compact and still supply a large population. It would take several square metres of solar cells to supply a small household. Alternatively, people sometimes talk about how concentrated or dilute an energy resource is. When talking about fuels, they are comparing how much energy is stored in a certain mass of the fuel. Particularly when comparing wind turbines with other energy resources, people will talk about the land area required to generate the same amount of energy.

Environmental impact

The use of fossil fuels leads to climate change.
A hydroelectric dam may flood useful farmland.
Every energy source has some effect on the environment.

Table P2.05 summarises some advantages and disadvantages of energy resources.

Energy resource	Advantages	Disadvantages
Solar	Renewable. Does not contribute to global warming. Useful in remote locations. No fuel cost.	Unreliable because the intensity of sunlight varies (and drops to zero at night). A large area of solar panels is required to capture the energy. Expensive initial building costs.
Wind	Renewable. Does not contribute to global warming. No fuel cost.	Unreliable because the speed of the wind can vary and on calm days no power is produced. Wind is a dilute energy resource. It would take a 'wind farm' of several hundred wind turbines to produce the same energy as a typical fossil fuel power station. Can be noisy and some people think they spoil the appearance of places where they are located. Expensive initial building costs.

(continued)

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Energy resource	Advantages	Disadvantages
Waves	Renewable. Does not contribute to global warming. No fuel cost.	Unreliable because the height of waves can vary and, when there are no waves, no power is produced. The cost is high because these machines corrode in the saltwater and can be damaged in storms.
Hydroelectric	Renewable. Does not contribute to global warming. Safe, clean and reliable. Very short start up time – this means energy can be supplied quickly to meet peaks in demand. No fuel cost.	Expensive initial building costs. Building dams and reservoirs floods land. People may be made homeless, and wildlife habitats destroyed.
Biofuels	Renewable. Does not contribute to global warming. It is reliable because it can be burnt when needed.	Burning fuels indoors for heating and cooking can affect health. Land is sometimes used to grow biofuels for profit rather than food.
Fossil fuels	Produce a large amount of energy. Fossil fuel power stations are reliable as we can burn more fuel when more electricity is needed.	Not renewable. Burning fossil fuels releases carbon dioxide into the atmosphere. This adds to the greenhouse effect and is the cause of recent global warming. Coal produces more carbon dioxide than oil and natural gas. Burning coal and oil usually also produces sulfur dioxide, which leads to acid rain and damage to ecosystems and buildings.
Nuclear	Provides a lot of energy from a small mass of fuel. It is a very concentrated store of energy in the form of nuclear energy. A typical nuclear power station will receive about one truckload of new fuel each week.	Not renewable. Waste is radioactive. Accidents at power stations can be catastrophic. Power stations are expensive to build and to decommission.
Geothermal	Renewable. Does not contribute to global warming. No fuel cost.	Only available at a few places on Earth where hot rocks are close enough to the surface.
Tidal	Renewable. Does not contribute to global warming. Tides are predictable making it a fairly reliable energy resource. No fuel cost.	Expensive initial building costs. Flooding estuaries to build tidal power stations can destroy wetlands, an important habitat for wildlife, particularly migrating birds that use it to feed and rest before the next leg of their journey. The barrage can also block shipping routes.

Table P2.05: Advantages and disadvantages of energy resources.

Questions

P2.24 Explain why wind power can be traced back to sunlight.

P2.25 List *one* advantage and *one* disadvantage of solar power.

P2.26 Explain why using fossil fuels is damaging to the environment.

P2.27 List the advantages and disadvantages of nuclear power.

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ACTIVITY P2.02

Sanghera Island

Sanghera Island (Figure P2.19) is a remote fictitious island. It has no fossil fuels. It is hot, with jungle vegetation, though it can sometimes be cold at night. High rainfall and mountainous terrain lead to fast-flowing streams. You are one of 25 members of a scientific expedition planning to study the island for three years. At the same time as minimising your impact (ecological footprint) on the island, you are the expert given the job of providing all the energy the team will need.

Answer the following questions to develop a plan that you will present to the team.

1. Describe *two* ways of providing hot water and heat for the buildings (living accommodation and laboratory).
2. Describe *two* possible ways of supplying heat for cooking food.
3. How would you supply the electricity needed for lighting, PCs and machinery?
4. There will be a refrigerator for life-saving medicines, as well as chemicals, that need to be stored at a constant temperature. How would you ensure a constant supply of electricity?
5. Which natural resource on the island should be conserved?
6. On a copy of the map, mark where you plan to locate buildings and the energy harvesters (devices that collect energy from the environment), showing how you would get the energy from the harvesters to the buildings, if necessary. Explain your reasons for choosing these particular sites.
7. Would your answers be different if the team had a limited budget? Explain your answer.
8. Describe what other information you might need before you can make a recommendation to the team.

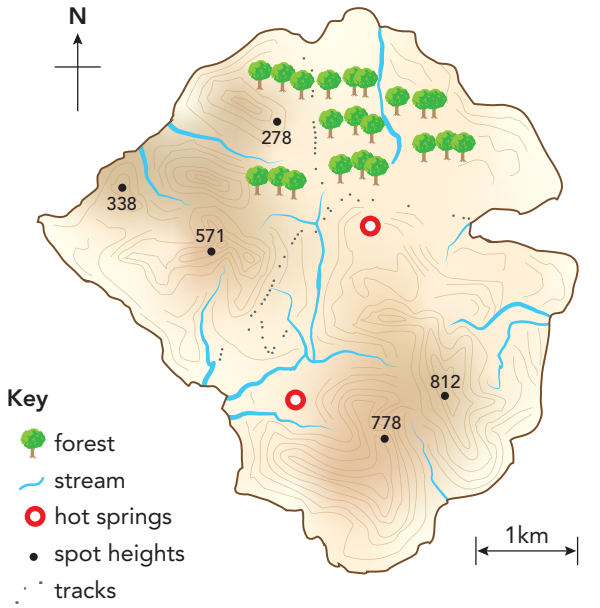

Figure P2.19: Map of Sanghera Island.

Reflection

Is there an effective method for memorising the different energy resources? For example, could you put them into categories? How will you learn their advantages and disadvantages?

Where does our energy come from?

As we have seen, most of the energy we use can be traced back to radiation from the Sun. Three exceptions to this are tidal energy, nuclear power and geothermal.

Tidal energy

The Moon and the Sun both contribute to the oceans' tides, though the effect of the Moon is greater as it is much nearer to the Earth. Their gravitational pull causes the level of the ocean's surface to rise and fall every twelve-and-a-bit hours. At high tide, water can be trapped behind a dam. Later, at lower tides, it can be released to drive turbines and generators.

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Nuclear power

Nuclear power makes use of nuclear fuels – mostly uranium – mined from underground. Uranium is a slightly radioactive element, which has been in the ground ever since the Earth formed, together with the rest of the Solar System, 4.5 billion years ago. Energy is released when nuclei split (nuclear fission).

Geothermal energy

Geothermal energy also depends on the presence of radioactive substances inside the Earth. These have been there since the Earth formed; they have been continuously releasing their store of energy ever since.

Harnessing nuclear power

Nuclear fusion

The Sun releases vast amounts of energy, but it is not burning fuel in the same way as we have seen for fossil fuels. It is not a chemical reaction. The Sun consists largely of hydrogen, but there is no oxygen to burn this gas. Instead, energy is released in the Sun by the process of nuclear fusion. In **nuclear fusion** nuclei join together and energy is released.

Nuclear fusion requires very high temperatures and pressures which are very hard to achieve on Earth. Scientists are working to make nuclear fusion a practical energy source on Earth. This would give us a huge source of clean energy.

Nuclear fission

Nuclear power stations use the energy produced in nuclear fission reactions. A large nucleus splits into smaller nuclei and energy is released. The products of nuclear fission are often radioactive for a long time, so dismantling a power station at the end of its life, and dealing with waste are major issues.

KEY WORDS

nuclear fusion: the process by which energy is released when two small light nuclei join together to form a new heavier nucleus.

Question

P2.28 What is the difference between nuclear fusion and nuclear fission?

P2.04 Doing work

Figure P2.20 shows one way of lifting a heavy object. Pulling on the rope raises the heavy box. As you pull, the force moves the box upwards.

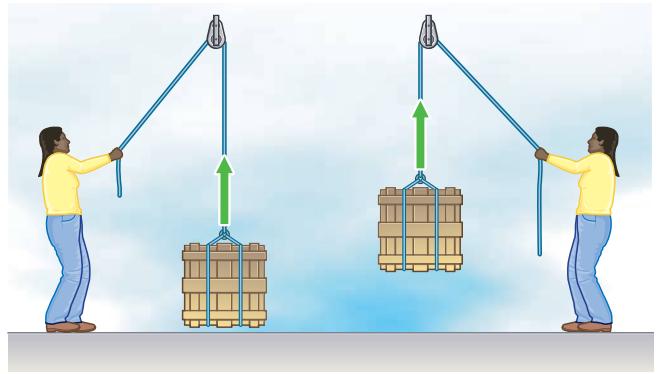

Figure P2.20: Lifting an object requires an upward force, pulling against gravity. As the box rises upwards, the force also moves upwards. Energy is being transferred by the force to the box.

To lift an object, you need a store of energy (as chemical energy, in your muscles). You give the object more gravitational potential energy. The force is your means of transferring energy from you to the object. This type of energy transfer by a force is called doing mechanical work.

Work is also done when an electric current flows around a circuit, for example to light a lamp. This is known as electrical work.

The more work that a force does, the more energy it transfers. The amount of **work done** is simply the amount of energy transferred:

work done = energy transferred

KEY WORDS

work done: the amount of energy transferred when one body exerts a force on another; the energy transferred by a force when it moves:
work done = energy transferred.

Three further examples of forces doing work are shown in Figure P2.21.

Mechanical or electrical work is equal to energy transferred. In this chapter, we are focusing on mechanical work.

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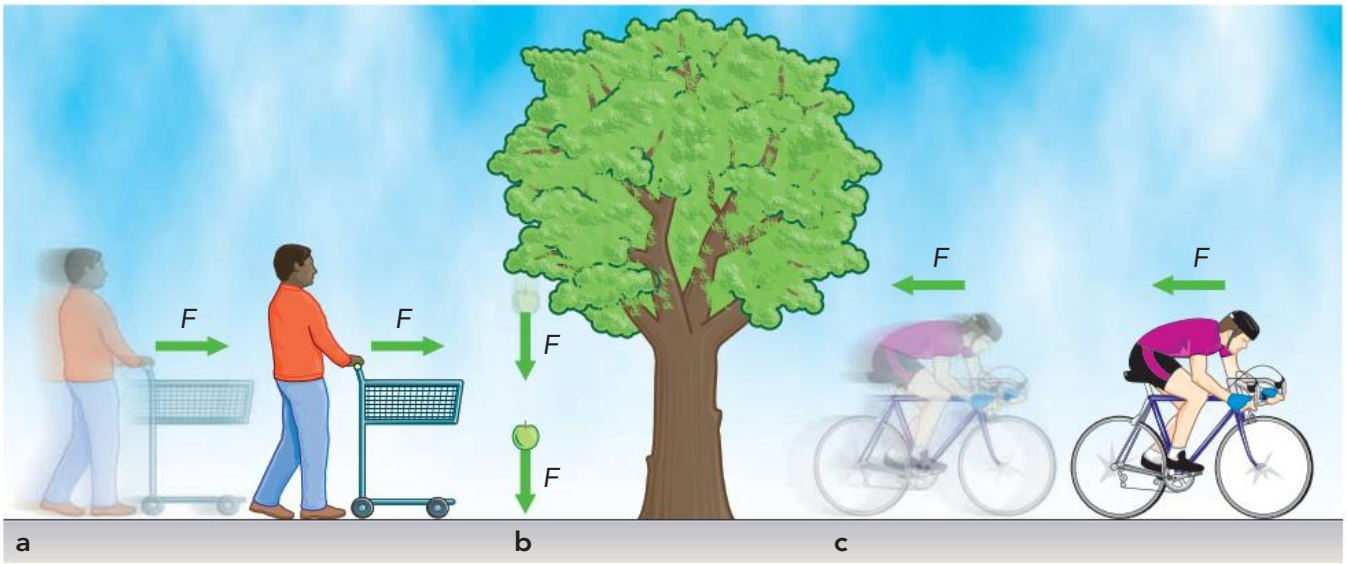

Figure P2.21: Three examples of forces doing work. In each case, the force moves as it transfers energy. **a:** Pushing a shopping trolley to start it moving. The pushing force does work. It transfers energy to the trolley, and the trolley's kinetic energy increases. **b:** An apple falling from a tree. Gravity pulls the apple downwards. Gravity does work, and the apple's kinetic energy increases. **c:** Braking to stop a bicycle. The brakes produce a force of friction, which slows down the bicycle. The friction does work, and the bicycle's kinetic energy is transferred to the internal energy of the brakes, which get hot.

How much work?

Think about lifting a heavy object, as shown in Figure P2.20. A heavy object needs a big force to lift it. The heavier the object is, and the higher it is lifted, the more its gravitational potential energy increases. This suggests that the amount of energy transferred by a force depends on two things:

- the size of the force: the greater the force, the more work it does
- the distance moved in the direction of the force: the further it moves, the more work it does.

So a big force moving through a big distance does more work than a small force moving through a small distance.

Words in physics

You will by now understand that 'work' is a word that has a specialised meaning in physics, different from its meaning in everyday life. When physicists think about the idea of work, they think about forces causing movement. Consider the students in Figure P2.22. The older student is reading and thinking, but no forces are involved (until she lifts a book or starts writing). She is not doing work. The younger girl has lifted the books up. She has done work against gravity.

Figure P2.22: Who is doing more work? The older student has not used a force to move anything. According to the physics definition of work, she has done no work against gravity. The younger student has lifted the books against the pull of gravity, so has done work.

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Many words have specialised meanings in science. It is important for physicists to agree on the terms they are using.

In Chapter P1, we saw that mass and weight are different, though in everyday language they are used to mean the same thing – how heavy something is. This is not a problem, provided you know whether you are using a particular word in its scientific sense or in a more everyday sense.

Questions

P2.29 Which of the following involve work being done?

- **a** A weightlifter holds a weight stationary for a minute.
- **b** A boy pushes as hard as he can against a door that will not open.
- **c** A baby lifts up a spoon.

P2.30 A girl carries a box up a flight of stairs. Name *two* factors which affect the amount of work she does.

Calculating work done

When a force does work, it transfers energy to the object it is acting on. The amount of energy transferred is equal to the amount of work done. We can write this as a simple equation:

$$W = \Delta E$$

In this equation, we use the symbol Δ (Greek capital letter delta) to mean 'amount of' or 'change in'. So,

$$\Delta E = \text{change in energy}$$

How can we calculate the work done by a force? The work done depends on two things:

- the size of the force, F
- the distance, d, moved by the force.

KEY EQUATION

Mechanical work done = force × distance moved by the force in the direction of the force

by a force

$$W = Fd = \Delta E$$

The phrase 'in the direction of the force' will be explained shortly. As the amount of work done is the same as the amount of energy transferred, it is measured in joules (J), the SI unit of energy.

Joules and newtons

The equation for the work done by a force ($W = F \times d$) shows us the relationship between joules and newtons. If we replace each quantity in the equation by its SI unit, we get 1 J = 1 N × 1 m = 1 Nm. So, a joule is a newton metre.

WORKED EXAMPLE P2.04

A crane lifts a crate upwards through a height of 20 metres. The lifting force provided by the crane is 5.0 kN, as shown in Figure P2.23.

- **a** How much work is done by the force?
- **b** How much energy is transferred to the crate?

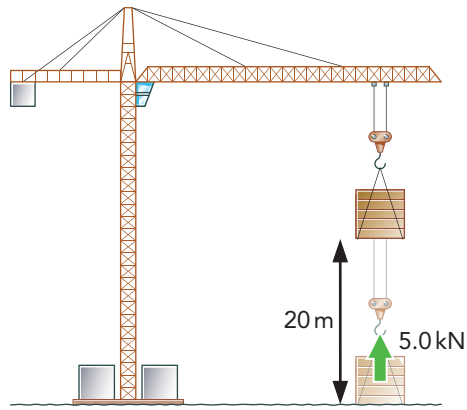

Figure P2.23: A crane lifts a crate upwards.

Step 1: Write down what you know, and what you want to know.

$F = 5.0\,\text{kN} = 5000\,\text{N}$

$d = 20\,\text{m}$

$W = ?$

Step 2: Write down the equation for work done, substitute values and solve.

$W = F \times d = 5000\,\text{N} \times 20\,\text{m}$

$= 100\,000\,\text{Nm} \equiv 100\,000\,\text{J}$

Answer

- **a** The work done by the force is 100 000 J, or 100 kJ.
- **b** Since work done = energy transferred, 100 kJ of energy is transferred to the crate.

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Work done and *mgh*

Worked example P2.04 illustrates an important idea. The force provided by the crane to lift the crate must equal the crate's weight, *mg*. It lifts the crate through a height, *h*. Then the work it does is force × distance, or *mg* × *h*. The gain in gravitational potential energy of the crate is *mgh*. This explains where the equation for gravitational potential energy comes from.

In Figure P2.24, the child slides down the ramp. Gravity pulls her downwards and makes her speed up. To calculate the work done by gravity, we need to know the vertical distance, *h*, because this is the distance moved in the direction of the force. If we calculated the work done as weight × distance moved down the ramp, we would get an answer that was too large. Now you should understand why we write the definition of work done like this:

KEY EQUATION

work done = force × distance moved in the direction of the force

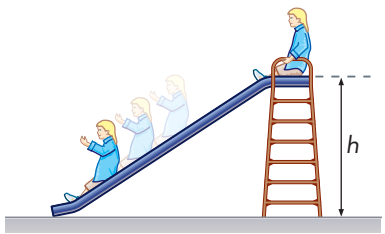

Figure P2.24: It is important to use the correct distance when calculating work done by a force. Gravity makes the child slide down the slope. However, to calculate the energy transferred by gravity, we must use the vertical height moved.

Forces doing no work

If you sit still on a chair (Figure P2.25), there are two forces acting on you. These are your weight, *mg*, acting downwards, and the upward contact force, *C*, of the chair, which stops you from falling through the bottom of the chair.

Neither of these forces is doing any work on you. The reason is that neither of the forces is causing movement, so you do not move through any distance, *d*. From $W = F \times d$, the amount of work done by each force is zero. When you sit still on a chair, your energy does not increase or decrease as a result of the forces acting on you.

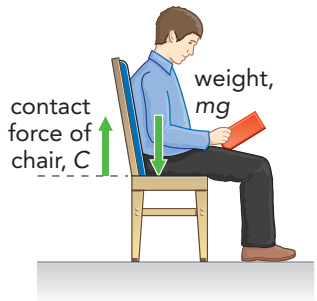

Figure P2.25: When you sit still in a chair, there are two forces acting on you. Neither transfers energy to you.

WORKED EXAMPLE P2.05

A girl can provide a maximum pushing force of 200 N. To move a box weighing 400 N onto a platform, she uses a plank as a ramp, as shown in Figure P2.26.

a How much work does she do in raising the box?

b How much gravitational potential energy does the box gain?

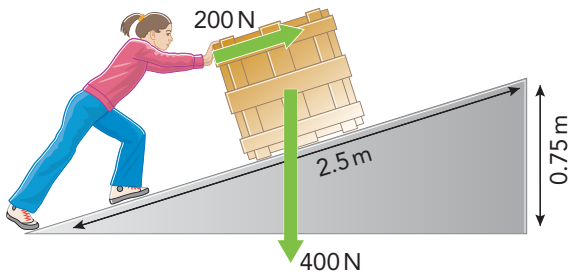

Figure P2.26: Doing work against gravity.

Step 1: Write down what you know, and what you want to know.

pushing force along the ramp, $F = 200\,\text{N}$

distance moved along ramp, $d = 2.5\,\text{m}$

weight of box downwards, $mg = 400\,\text{N}$

vertical distance moved, $h = 0.75\,\text{m}$

work done along the ramp, $W = ?$

gravitational energy gained, $\Delta E_p = ?$

Step 2: Calculate the work done, *W*, by the pushing force along the ramp.

W = pushing force along ramp × distance moved along ramp

$= F \times d$

$= 200\,\text{N} \times 2.5\,\text{m}$

$= 500\,\text{J}$

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CONTINUED

Step 3: Calculate the gain in gravitational potential energy of the box. This is the same as the work done against gravity, ΔE_p.

$\Delta E_p = mg\Delta h$

We know that weight = mg, so this becomes:

$\Delta E_p = W \times \Delta h$

$= 400\,\text{N} \times 0.75\,\text{m}$

$= 300\,\text{J}$

Answer

a The girl does 500 J of work in raising the box.

b The box gains 300 J in gravitational potential energy.

Note: Only 300 J is transferred to the box. The remaining 200 J is the work done against friction as the box is pushed along the slope.

Questions

P2.31 A boy pulls a sled (at a constant speed) with a force of 50 N for a distance of 250 metres. How much work does the boy do?

P2.32 A 100 g apple falls from a tree and lands on the ground 6 metres below.

a What is the force that is pulling the apple, and how large is the force?

b Calculate how much work gravity does on the apple as it falls.

c What energy transfer is taking place?

P2.05 Power

Exercising in the gym (Figure P2.27) can put great demands on your muscles. Speeding up a treadmill means that you have to work harder to keep up. Equally, your trainer might ask you to find out how many times you can lift a set of weights in one minute. These exercises are a test of how powerful you are. The faster you work, the greater your **power**.

KEY WORD

power: the rate at which work is done, or the rate at which energy is transferred.

Figure P2.27: At the gym, it is easier to lift small loads, and to lift them slowly. The greater the load you lift and the faster you lift it, the greater the power required. It is the same with running on a treadmill. The faster you have to run, the greater the rate at which you do work.

In physics, the word power is used with a special meaning. It means the rate at which you do work (that is, how fast you work). The more work you do, and the shorter the time in which you do it, the greater your power. Power is the rate at which energy is transferred, or the rate at which work is done.

Fast working

Power tells you about the rate at which a force does work, that is the rate at which it transfers energy. When you lift an object up, you are transferring energy to it. Its potential energy increases. You can increase your power by:

- lifting a heavier object in the same time
- lifting the object more quickly.

It is not just people who do work. Machines also do work, and we can talk about their power in the same way.

- A crane does work when it lifts a load. The bigger the load and the faster it lifts the load, the greater the power of the crane.
- A locomotive pulling a train of coaches or wagons does work. The greater the force with which it pulls and the greater the speed at which it pulls, the greater the power of the locomotive.

Question

P2.33 Your neighbour is lifting bricks and placing them on top of a wall. He lifts them slowly, one at a time. Suggest *two* ways in which he could increase his power (the rate at which he is transferring energy to the bricks).

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ACTIVITY P2.03

The meaning of work and power

Work and power have very specific meanings in physics. You will create a resource that helps people understand their correct meanings in physics. You could start by collecting definitions that are wrong in physics. For example, collect images of powerful people or cars, or an image of a gymnast performing the 'iron cross' (Figure P2.28). If you are feeling creative, you could write a poem or create a song or podcast.

- Work for a few minutes in small groups to discuss ideas and choose one idea to develop.
- Develop your idea within the timeframe given by your teacher.
- If the class is divided into two or three large groups, you will perform or present your idea to the other pairs or threes in your group.
- Vote on the other presentations. A pair or three cannot represent their group unless the physics is correct, so help correct any physics mistakes.
- The pair or three chosen by each group will present to the rest of the class.

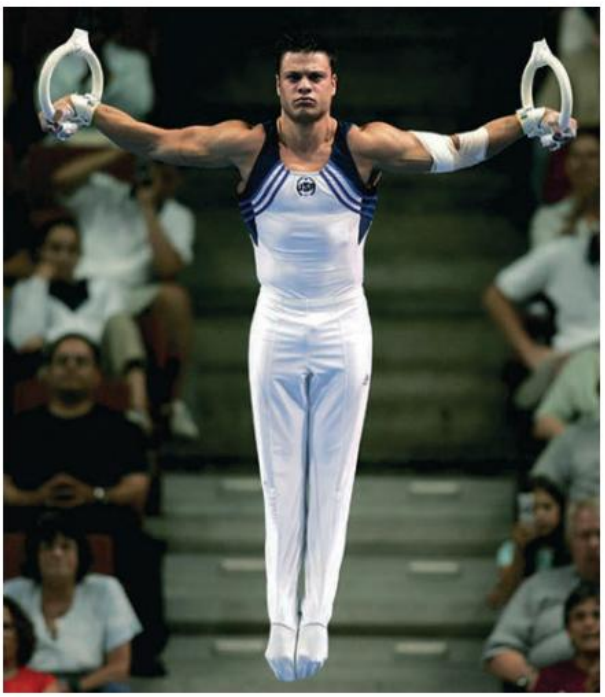

Figure P2.28: This gymnast is performing the 'iron cross' on rings. It is a move that requires tremendous strength in the core, arms and wrists. But is he doing any work from a physics point of view?

Calculating power

Power is the rate at which work is done, or the amount of work done in each second. Since work done is equal to energy transferred, we can write these ideas about power as equations, as shown.

KEY EQUATIONS

$$\text{power} = \frac{\text{work done}}{\text{time taken}}$$

$$p = \frac{W}{t}$$

$$\text{power} = \frac{\text{energy transferred}}{\text{time taken}}$$

$$p = \frac{\Delta E}{t}$$

Units of power

Power is measured in **watts (W)** . One watt (1 W) is the power when one joule (1 J) of work is done per unit time. So one watt is one joule per second.

- 1 W = 1 J/s
- 1000 W = 1 kW (kilowatt)
- 1 000 000 W = 1 MW (megawatt)

Take care not to confuse W for work done (or energy transferred) with W for watts. In books, the first of these is shown in italic type (as here), but you cannot usually tell the difference when they are handwritten. SI units are often related to each other. It is useful to remember some of the connections, such as 1 J = 1 Nm and 1 W = 1 J/s.

KEY WORD

watt (W): the unit of power when 1 J of work is done per unit time; 1 W = 1 J/s.

Power in general

We can apply the idea of power to any transfer of energy. For example, electric light bulbs transfer energy supplied to them by electricity. They transfer energy by light and heating. Most light bulbs are labelled with their power rating – for example, 40 W, 60 W, 100 W – to tell the user about the rate at which the bulb transfers energy.

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Percentage efficiency

We can express the efficiency of a light bulb or any other energy-changing device in terms of the power it supplies:

$$\text{percentage efficiency} = \frac{\text{useful power output}}{\text{power input}} \times 100\%$$

Remember how this compares with the equation for energy efficiency in terms of energy:

$$\text{percentage efficiency} = \frac{\text{useful energy output}}{\text{energy input}} \times 100\%$$

WORKED EXAMPLE P2.06

A car of mass 800 kg accelerates from rest to a speed of 25 m/s in 10 s. What is its power?

Step 1: Calculate the work done. This is the increase in the car's kinetic energy.

$$E_K = \frac{1}{2}mv^2$$
$$= \frac{1}{2} \times 800\ \text{kg} \times (25\ \text{m/s})^2$$
$$= 250\,000\ \text{J}$$

Step 2: Calculate the power.

$$\text{power} = \frac{\text{work done}}{\text{time taken}}$$
$$= \frac{250\,000\ \text{J}}{10\ \text{s}}$$
$$= 25000\ \text{W} \equiv 25\ \text{kW}$$

Answer

The energy is being transferred to the car (from its engine) at a rate of 25 kW, or 25 kJ per second.

Car engines are not very efficient. In this example, the car's engine may transfer energy at the rate of 100 kW or so, although most of this is wasted as thermal energy.

REFLECTION

Do you find the problem-solving strategy in the worked examples useful?

Do you use it all the time?

Do you have a better approach?

Questions

P2.34 **a** How many watts are there in a kilowatt?

b How many watts are there in a megawatt?

P2.35 A light bulb transfers 1000 J of energy in 10 s. What is its power?

P2.36 An average man needs to eat food containing about 2500 kcal of chemical potential energy per day (1 kcal = 4.18 kJ).

a What is 2500 kcal expressed in joules?

b Calculate the power output of the average man, even when he is doing no work.

P2.37 It is estimated that the human brain has a power requirement of 40 W. How much energy does it use in an hour?

ACTIVITY P2.04

Revision boomerang

You will be in a group of three. Your teacher will let you know how much time you have to draw a mind map on a sheet of A3. It should include all the key terms, concepts and equations related to energy. Use pictures to illustrate the ideas where possible, but your mind map should include:

- the principle of conservation of energy and the various energy stores and energy transfers
- the various energy resources (which ones depend on sunlight, which are renewable, and so on)
- any equations (both word and symbol) you need to know (include units in pencil or a different colour).

When your teacher tells you to, pass your mind map to the person on your left. You receive a mind map from the person on your right. Your job is to correct any mistakes and add missing information.

When your teacher tells you, the mind maps will change hands a second time. Correct and add as before.

The next time your teacher asks you to pass on the mind maps, your own mind map should arrive back with you.

Self assessment

Did you know most of the information for Activity P2.06, or did your classmates need to add a lot of missing information?

If you could not remember as much as you thought you would, you need to develop a strategy to help you learn the material (for example, by developing a set of flash cards).

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PROJECT P2.01 IMPROVING LIVES WITH ENERGY

Choose one of the options below and either produce a short report (fewer than 500 words) along with relevant illustrations or produce a short presentation (two or three minutes), with suitable visual aids.

Option 1: Inventions for remote places

Research an invention that provides useful energy in a location without an obvious or reliable energy supply. If you cannot track down another invention, focus on one of the following examples.

- PlayPump is a system that uses a children's roundabout to power a water pump.
- Trevor Baylis invented the wind-up radio, (Figure P2.29) which worked without batteries or access to an electrical power source.

Option 2: Efficiency

It is important to increase efficiency to reduce waste, reduce environmental damage, and save money. Investigate efforts to improve the efficiency of one device (for example, a light bulb, or a car) or create better insulation for homes.

Figure P2.29: A wind-up radio.

SUMMARY

Energy can be stored in different ways and can be transferred between stores.
A moving object has a store of kinetic energy.
Heating a body will increase its internal energy.
Changing the shape of a body will change its elastic (strain) energy.
Lifting a body will increase its gravitational potential energy.
Food and fuels are stores of chemical energy.
Mechanical work can transfer gravitational potential energy to an object, by lifting it.
Electric currents transfer energy electrically.
Energy is conserved. It cannot be created or destroyed; it can only transfer from one store to another.
Efficiency is the fraction of the total energy that is useful.
When a process is not 100% efficient, the wasted energy spreads out (usually increasing the thermal energy store of the surroundings) and is not useful.

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CONTINUED

change in gravitational potential energy = weight × change in height or change in gravitational potential energy = mass × gravitational field strength × change in height or $\Delta E_p = mg\Delta h$.
Kinetic energy is $E_k = \frac{1}{2}mv^2$.
The energy we use can come from a variety of resources: fossil fuels, biofuels, water, geothermal, nuclear, solar and wind.
Some energy resources are used directly, others transfer energy to electrical energy using turbines and generators.
Solar cells (also known as photocells) generate electricity using energy from the Sun.
Oil, coal and natural gas are all examples of fossil fuels.
Non-renewable energy resources will run out. This includes fossil fuels and nuclear fuel, but not biofuel.
Biofuels are renewable, reliable, cheap to set up and use, but are diffuse.
Geothermal energy is harvested (collected) where hot rock is close to the Earth's surface.
Wind power, wave power and solar power are renewable but unreliable and dilute energy resources. Running costs are low but they are expensive to set up.
Hydroelectric power, tidal power and geothermal power are renewable, reliable and concentrated energy resources but suitable locations are limited, and they are expensive to set up.
Nuclear power stations use nuclear fuel, which produces thermal energy by nuclear fission when heavy nuclei break apart.
The Sun is the origin of all our energy resources except geothermal, nuclear and tidal.
The source of the Sun's energy is nuclear fusion, when hydrogen fuses (joins) together to form helium.
The Moon is the main source of tidal energy.
Work is done when a force causes something to move.
The amount of work done depends on the distance moved in the direction of the force; the further it moves, the more work is done.
The amount of work done is equal to the amount of energy transferred.
work done = force × distance moved in the direction of the force
power = energy transferred ÷ time taken = work done ÷ time taken

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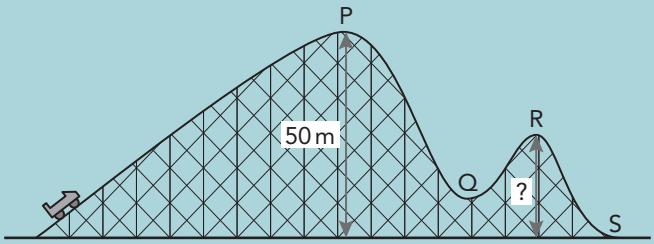
PRACTICE QUESTIONS

Use this diagram for questions 1 and 2

This diagram shows an amusement park roller coaster ride (not drawn to scale).



1 **Identify** which store of energy is greatest at point P.

A gravitational potential energy
B kinetic energy
C elastic energy
D chemical energy **[1]**

2 Identify which store of energy increases as the cart moves from point P to point Q.

A gravitational potential energy
B kinetic energy
C elastic energy
D chemical energy **[1]**

3 **State** the principle of conservation of energy. **[1]**

4 **Give** *one* renewable and *one* non-renewable energy resource. **[2]**

5 Copy and complete these sentences. Choose words from this list.

work **energy** **more** **less**

a When a force makes an object move, _____ is done. **[1]**

b The greater the distance an object is moved by the force, the _____ work it does. **[1]**

c Power is the rate at which _____ is transferred. **[1]**

d A low-powered motor will transfer ____ energy each second than a more powerful motor. **[1]**

[Total: 4]

6 State the SI units for:

a energy **[1]**

b work **[1]**

c power **[1]**

[Total: 3]

COMMAND WORD

identify: name/select/recognise.

COMMAND WORDS

state: express in clear terms.

give: produce an answer from a given source or recall/memory.

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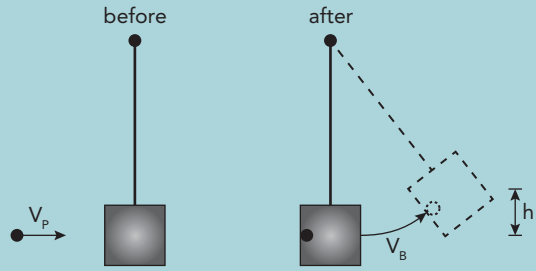
CONTINUED

7 Scientists use a ballistic pendulum to work out the speed of a projectile that hits it. The block has a mass of 4.7 kg and moves with an initial speed of 1.24 m/s when it is hit.



a State the equation linking kinetic energy, mass and velocity. **[1]**

b **Calculate** the kinetic energy of the block. **[2]**

c As the block swings, it gains gravitational potential energy. State the maximum gravitational potential energy that can be gained by the block. **[1]**

d State the equation linking gravitational potential energy, mass, gravitational field strength and height. **[1]**

e Calculate the maximum height the block gains. **[2]**

[Total: 7]

8 A coal-fired power station and a wind turbine both produce electrical power. The power station produces 2500 MW and the wind turbine produces 2.0 MW.

a State *one* advantage of using wind turbines instead of a coal-fired power station to produce electricity. **[1]**

b Coal-fired power stations still account for one-third of the world's energy consumption. **Explain** why wind turbines have not replaced them. **[2]**

[Total: 3]

9 The Empire State Building in New York is the venue for an annual running competition. Competitors race up 86 floors (1576 stairs) or 320 metres to finish close to the top. The record fastest time is 9 minutes 33 seconds by Paul Crake in 2003. His mass was 62.5 kg.

a Calculate Paul Crake's weight. **[1]**

b State the relationship between work done, force and distance. **[1]**

c Calculate the work done by Paul Crake. Express your answer in kJ (1 kJ = 1000 J). **[1]**

d State the relationship between power, work done, and time. **[1]**

e Calculate Paul Crake's average power output during his record-breaking run. **[1]**

[Total: 5]

COMMAND WORD

calculate: work out from given facts, figures or information.

COMMAND WORD

explain: set out purposes or reasons/make the relationships between things clear/say why and/or how and support with relevant evidence.

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SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
identify different energy stores	P2.01			
describe how energy is transferred between stores	P2.01			
describe what is meant by efficiency	P2.02			
calculate efficiency	P2.02			
state and explain the principle of conservation of energy	P2.02			
recall and use the equation to calculate kinetic energy	P2.02			
recall and use the equation to calculate gravitational potential energy	P2.02			
describe energy resources	P2.03			
describe how energy resources can be used to generate electricity	P2.03			
describe the advantages and disadvantages of different energy resources	P2.03			
describe how most of our energy resources depend on the energy supplied by the Sun and name the process by which the Sun releases this energy	P2.03			
name three energy resources which do not rely on the Sun	P2.03			
describe what is meant in physics by the word ‘work’	P2.04			
recall and use the equation to calculate work done	P2.04			
explain how the rate at which work is done is related to power	P2.05			
recall and use the equation to calculate power.	P2.05			

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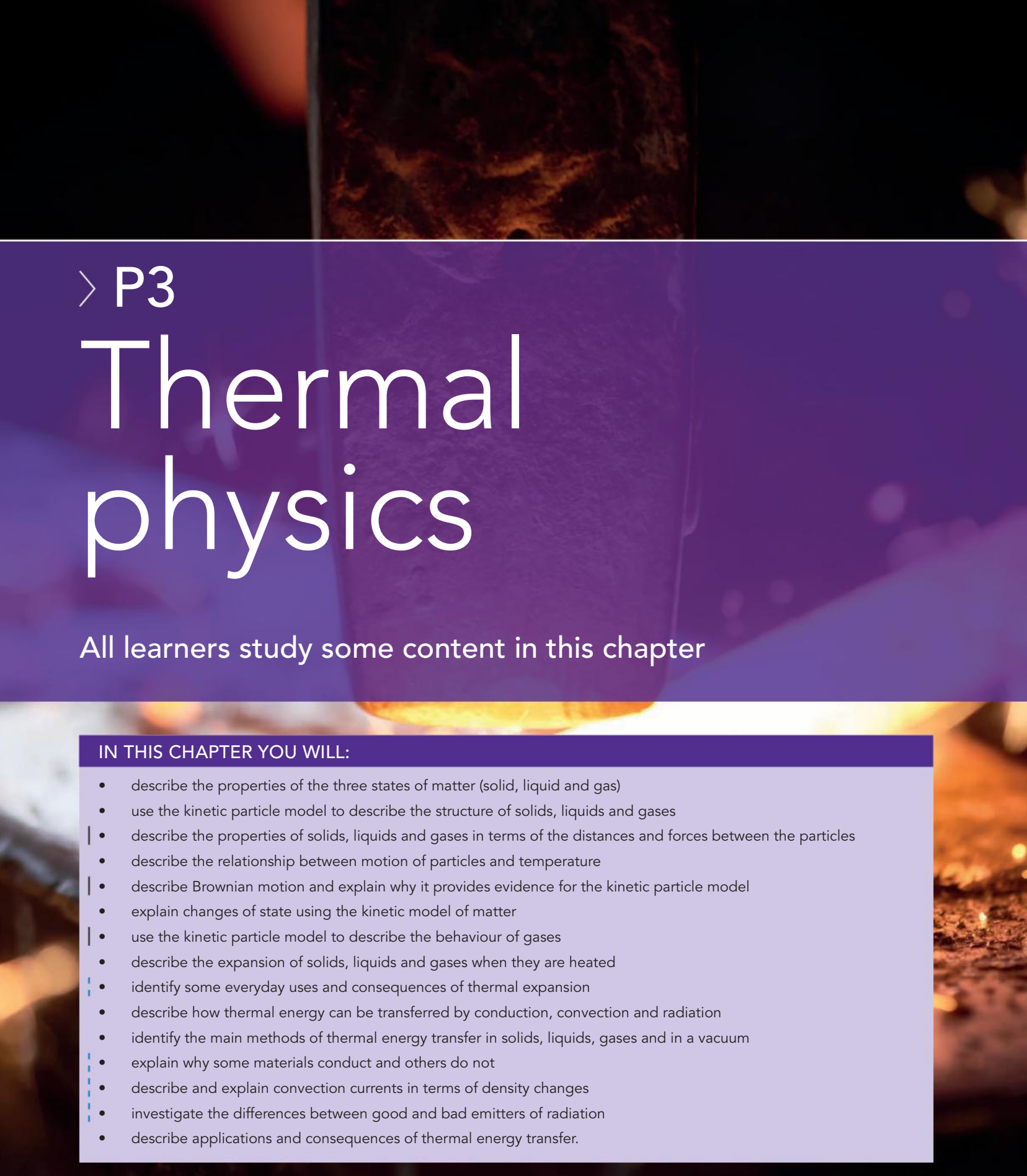

P3 Thermal physics

All learners study some content in this chapter

IN THIS CHAPTER YOU WILL:

- describe the properties of the three states of matter (solid, liquid and gas)
- use the kinetic particle model to describe the structure of solids, liquids and gases
- describe the properties of solids, liquids and gases in terms of the distances and forces between the particles
- describe the relationship between motion of particles and temperature
- describe Brownian motion and explain why it provides evidence for the kinetic particle model
- explain changes of state using the kinetic model of matter
- use the kinetic particle model to describe the behaviour of gases
- describe the expansion of solids, liquids and gases when they are heated
- identify some everyday uses and consequences of thermal expansion
- describe how thermal energy can be transferred by conduction, convection and radiation
- identify the main methods of thermal energy transfer in solids, liquids, gases and in a vacuum
- explain why some materials conduct and others do not
- describe and explain convection currents in terms of density changes
- investigate the differences between good and bad emitters of radiation
- describe applications and consequences of thermal energy transfer.

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BEFORE YOU START

Work with a partner. Take a large sheet of paper and write the words 'solid', 'liquid' and 'gas' on the paper.

Around each word, write as much as you can about that **state of matter**. You can include drawings.

Using a different-coloured pen, make as many links as you can between the three words, as the example shows in Figure P3.01.

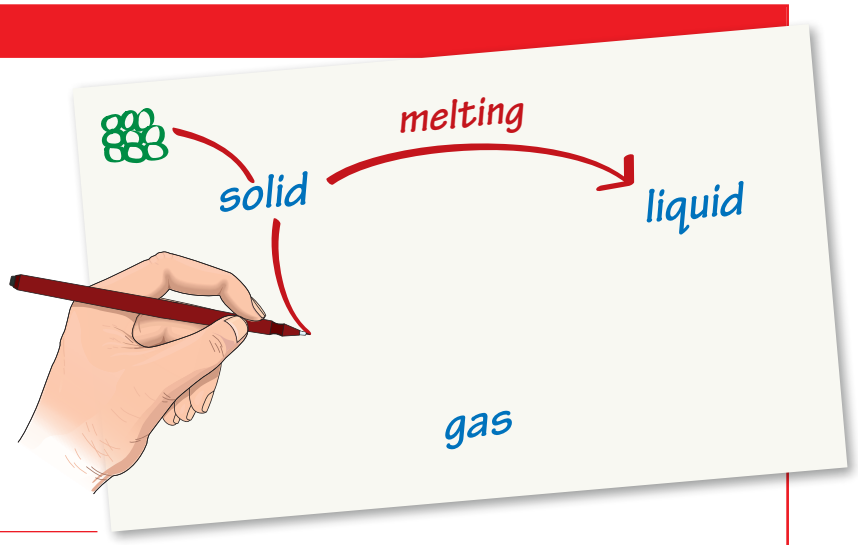

Figure P3.01: Making links between words.

KEY WORDS

states of matter: solid, liquid or gas.

SCIENCE IN CONTEXT P3.01

The strange behaviour of water

Most substances expand when they get hot and contract when they get cold. Water does not always follow this rule. Think about how a pond cools down in cold weather. As the air temperature drops, the water at the top of the pond is cooled by the cold air above it and contracts. This makes the water at the top of the pond more dense, so it sinks to the bottom. The coldest water will be at the bottom of the pond. If this continued, ice would form at the bottom of the pond.

Fortunately for the fish, water does not keep contracting. As it cools from 4 °C to 0 °C, the water expands. This means that the colder water is less dense than the water below it and so it remains at the top. This water continues to cool and eventually freezes. The ice forms at the top of the pond, not the bottom (Figure P3.02). This means fish can survive in the water beneath the ice. This property of water is called the anomalous expansion of water.

Unlike most substances, water is less dense as a solid (ice) than it is as a liquid. This means that ice floats in water. Most substances are more dense when they are solid and so do not float. This strange behaviour is caused by the hydrogen bonds in water which cause it to form a crystal structure with the particles in ice more spaced out than in water.

Figure P3.02: The water below the ice is cold, but not cold enough to freeze.

Discussion questions

1 Sketch a graph to show how the density of water changes from 0 to 10 °C.

2 Discuss what would happen to life on Earth if water froze like other liquids, so that ponds froze from the bottom up.

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P3.01 Kinetic particle model of matter

States of matter

Matter exists in three states: solid, liquid and gas. An example of this is water, which can exist as solid ice, liquid water or steam, which is an invisible gas. Steam quickly condenses in air to form tiny water droplets, which are what we see. We can describe these states by describing their shape and volume (size). Table P3.01 shows how these help us to distinguish between solids, liquids and gases.

Changes of state

Heat a solid and it melts to become a liquid. Heat the liquid and it boils to become a gas. Cool the gas and it becomes first a liquid and then a solid. The **changes of state**, **melting**, **evaporation** or **boiling**, **condensing** and **solidifying** are shown in Figure P3.03.

Questions

P3.01 Copy and complete these sentences:

The three states of matter are _____, _____ and _____.

A solid has a definite shape and _____. A liquid has a definite _____ but takes the shape of its container. A gas will expand to fill all the _____ available.

When a solid is heated it _____ to make a _____.

P3.02 To measure the volume of a liquid, you can pour it into a measuring cylinder. Measuring cylinders come in different shapes and sizes – tall, short, wide, narrow. Explain why the shape of the cylinder does not affect the measurement of volume.

KEY WORDS

changes of state: changing from one state of matter to another.

melting: changing from solid to liquid.

evaporation: changing from a liquid to a gas at any temperature.

boiling: changing from liquid to gas at a fixed temperature called the boiling point.

condensing: changing from gas to liquid.

solidifying: changing from liquid to solid.

	 Ice cubes have a fixed shape.	 This coloured water takes the shape of the flasks.	 The steam leaving the pot quickly condenses to form water droplets.
State	solid	liquid	gas
Size	rigid, fixed shape, fixed volume; cannot be squashed	not rigid, no fixed shape, fixed volume; cannot be squashed	not rigid, no fixed shape, no fixed volume; can be squashed
Shape	has a definite shape	takes the shape of its container	expands to fill its container

Table P3.01: The distinguishing properties of the three states of matter.

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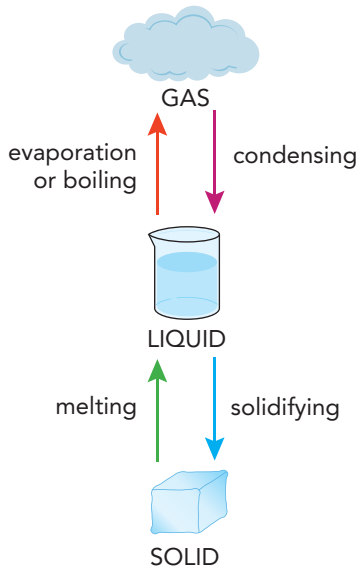

Figure P3.03: Naming changes of state.

Particle model

In this topic, we will use a **model** to help us explain the behaviour of materials. Scientists often use models to explain things that they cannot see directly. Using this model will help us answer questions such as:

- Why does an ice cube change shape as it melts?
- How can we smell perfume from across a room?
- Why does it take time to melt a solid?

The model is called the **kinetic particle model of matter**. The word 'kinetic' means related to movement. All matter is made up of tiny particles – **atoms**, **molecules** or ions (Figure P3.04).

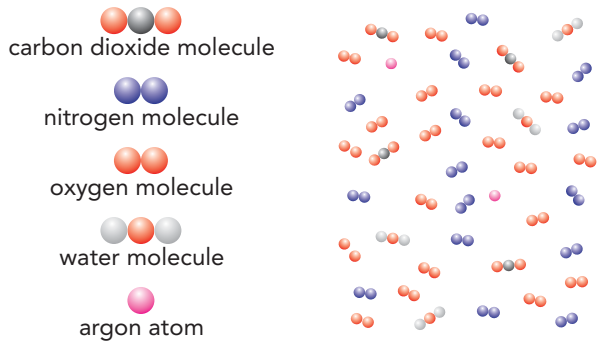

Figure P3.04: Air is a mixture of elements and compounds.

There are many different types of particles with different chemical properties. In this chapter we will look at how these particles move rather than how they react.

We will draw all the atoms and molecules as spheres and refer to them all as particles (Figure P3.05).

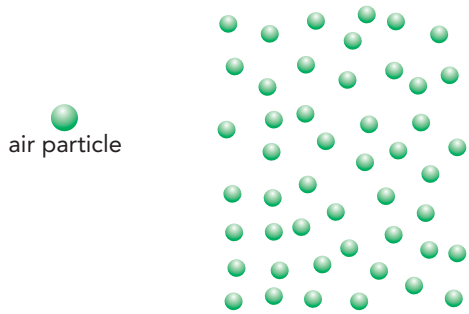

Figure P3.05: For this model we will assume all atoms and molecules are identical spherical particles.

The idea that matter is made up of identical, spherical molecules is a great simplification, but using this model will help to explain the behaviour of materials.

Describing the particle structure of solids, liquids and gases

Table P3.02 shows how we picture the particles in a solid, a liquid and a gas. Each state of matter can be described by describing the arrangement, separation and motion of its particles.

Particle movement and temperature

Kinetic theory uses the idea that, as particles heat up, they gain more kinetic energy and so move faster. As a substance cools down, its particles lose kinetic energy and slow down.

Forces and the kinetic model

We have seen that the kinetic model of matter can explain the differences between solids, liquids and gases. We can explain some other observations if we add another scientific idea to the kinetic theory: we need to consider the forces between the particles that make up matter.

KEY WORDS

model: a way of representing a system which we cannot experience directly.

kinetic particle model of matter: a model in which matter consists of moving particles.

atom: the smallest part of an element that can exist.

molecule: two or more atoms joined together by chemical bonds.

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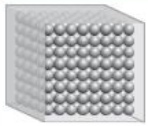
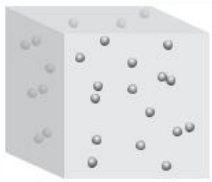
State	Arrangement and separation of particles	Motion of particles
 Solid	The particles are packed closely together, in a regular pattern. Notice that each particle is in close contact with all its neighbours.	Because the particles are so tightly packed, they cannot move around. However, they do move a bit. They can vibrate about a fixed position. The hotter the solid, the more they vibrate.
 Liquid	The particles are packed slightly less closely together than in a solid. The particles are arranged randomly rather than in a fixed pattern.	Because the particles are slightly less tightly packed than in a solid, they can move around. So the particles are both vibrating and moving from place to place. The hotter the liquid is, the faster its molecules move.
 Gas	The particles are widely separated from one another. They are no longer in contact, unless they collide with each other.	The particles move freely about, bouncing off one another and off the walls of the container.

Table P3.02: The arrangement and motion of particles in the three different states of matter.

Why do the particles that make up a solid or a liquid stick together? There must be **attractive forces** (forces pulling them together) between them. Without attractive forces to hold together the particles, there would be no solids or liquids, only gases. No matter how much we cooled matter down, it would remain as a gas. The attractive forces between particles have a short range, so are negligible in gases.

KEY WORDS

attractive forces: forces between particles which hold the particles in fixed positions in a solid and close together in a liquid.

Questions

P3.03 Sketch *three* diagrams to show the arrangement of molecules in a solid, a liquid and a gas.

P3.04
- **a** In which state of matter are the particles most closely packed?
- **b** In which state of matter are they most widely separated?
- **c** In which state do the particles move fastest?

Evidence for the kinetic model

Atoms and molecules are far too small to see, even with a microscope, but experiments show the effects of moving atoms and molecules. These experiments do not prove there are moving particles, but they do provide support for the idea.

In 1827, a scientist called Robert Brown was using a microscope to study pollen grains when he noticed tiny particles jiggling about. At first he thought that they might be alive, but when he repeated his experiment with tiny grains of dust suspended in water, he saw that the dust also moved around. This movement provides evidence for the kinetic particle theory.

The motion Brown observed is now known as **Brownian motion**, and it happens because the moving particles are constantly knocked about by the fast-moving particles of the air.

We can do a similar experiment using smoke particles. The oxygen and nitrogen molecules that make up the air are far too small to see, so we have to look at something bigger, and look for the effect of the air molecules.

We can use a smoke cell (Figure P3.06a). This is a small glass box which contains air with a small amount of smoke. The cell is lit from the side, and the microscope is used to view the smoke particles.

KEY WORDS

Brownian motion: the motion of small particles suspended in a liquid or gas, caused by molecular bombardment.

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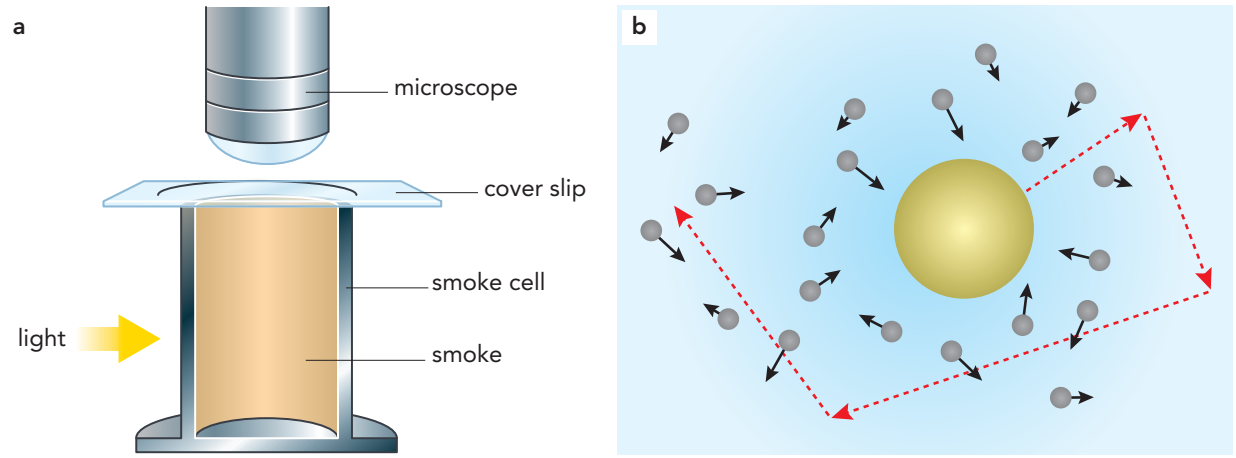

Figure P3.06 a: An experimental arrangement for observing Brownian motion. The smoke particles are just large enough to show up under the microscope. The air molecules that collide with them are much too small to see. **b:** The invisibly small air molecules repeatedly hit the smoke particle making it change direction. The dotted line shows the path of the smoke particle.

The smoke particles show up as tiny specks of light, but they are too small to see any detail of their shape. What is noticeable is the way they move. If you watch a single particle (P3.06b), you will see that it follows a random path, frequently changing direction. This is because air molecules repeatedly hit the smoke particle.

Explanations using the kinetic model

The kinetic model of matter can be used to explain many **observations**. Here are some of them:

- Liquids take up the shape of their container because their particles are free to move about within the liquid.
- Gases fill their container because their particles can move about with complete freedom.
- Solids keep their shape because the particles are packed tightly together.
- Gases diffuse (spread out) from place to place, so that, for example, we can smell perfume across the room. The perfume particles spread about because they are free to move.
- Dissolved substances diffuse throughout a liquid. Sugar crystals in a drink dissolve and molecules spread throughout the liquid, carried by the mobile particles. In a hotter drink, the particles are moving faster and the sugar diffuses more quickly.

KEY WORD

observations: what you see happening in an experiment.

ACTIVITY P3.01

Demonstrating the kinetic particle model

The kinetic theory can be modelled using small balls or marbles in a tray (Figure P3.07).

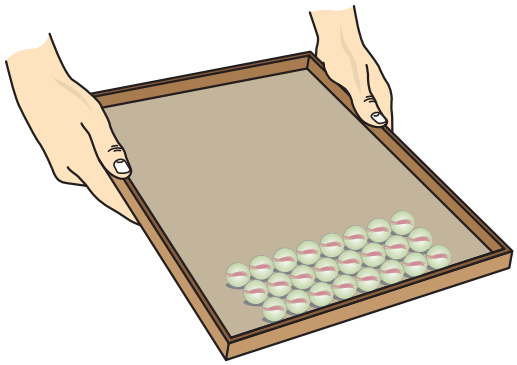

Figure P3.07: Demonstrating the kinetic particle model using marbles in a tray.

1. Place some identical small balls or marbles on a shallow tray. They should cover about one-quarter of the area of the tray.
2. Tip the tray slightly so that the balls all roll to the lower end. The pattern they form is like the arrangement of particles in a solid.
3. Keep the tray slightly tipped and shake it gently so that the balls can move about. This is like a liquid.
4. Keep shaking the tray and tip it so that it becomes horizontal. The balls move around freely, colliding with each other and the sides of the tray. This is like the particles in a gas.

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CONTINUED

Your task is to make a video, or a presentation to explain the kinetic model, using the tray of balls. You could:

- show the arrangement and movement of particles in each of the three states
- demonstrate and explain changes of state – melting, boiling, condensing and freezing
- model Brownian motion (hint: use a larger, different-coloured ball for the smoke particle)
- add some different-coloured balls to one corner of the tray to represent perfume; show how the perfume diffuses (spreads out).

Questions

P3.05 **a** Describe what is meant by Brownian motion.

b How can the kinetic particle model be used to explain Brownian motion?

c A student did an experiment to observe Brownian motion. She then repeated the experiment in a much colder room. Describe and explain how her observations would change.

P3.06 Use the kinetic particle model of matter to explain why we can walk through air and swim through water but we cannot walk through a solid wall.

P3.02 Pressure changes

The particles in a gas move about freely. The particles hit the walls of the container. The individual collisions are random, but due to the large number of collisions there is a fairly constant force on each unit area of the walls of the container. This is the pressure of the gas.

The kinetic model can help us understand how gases behave. Thinking about the particles in a gas helps us answer questions about the gas.

Table P3.03 shows why a gas causes pressure on the walls of its container, and the effect of changing temperature or volume.

The cyclist in Figure P3.08 needs to understand gas pressure. He pumps air into his tyres to make them hard. If the temperature rises, the pressure in his tyres will increase even more. This could burst his tyres.

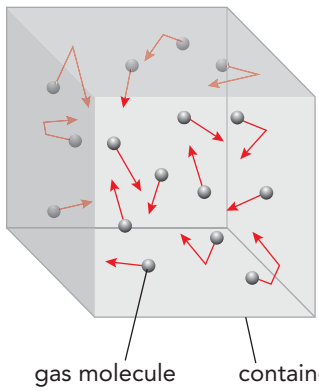
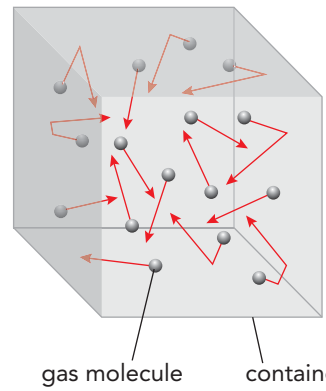
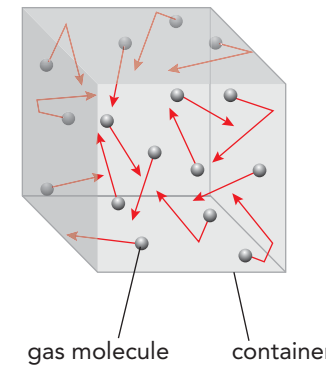
Gas in a container	Effect of heating the gas	Effect of compressing (squeezing) the gas
		
These are the particles that make up a gas. The particles of a gas move around inside its container, bumping into the sides. The gas causes pressure on the walls of the container because the gas particles are constantly colliding with the walls.	This shows the same gas at a higher temperature. The higher the temperature of a gas, the faster its particles are moving. The particles will hit the walls more often and with more force. This increases the pressure.	This is the same gas again. This time the volume of the container has been decreased. The gas has been compressed into a smaller space. The particles do not move as far between collisions, so they collide with the walls more often. Decreasing the volume of a gas increases its pressure.

Table P3.03: the effects of heating or compressing a gas.

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Figure P3.08: Pumping up tyres means squashing a lot more air particles into a fixed space. This increases the pressure.

Questions

P3.07 Copy and complete the paragraph.

The molecules in a _____ are constantly moving freely and rapidly and so hit the walls of the container.

This creates _____ on the walls.

When the gas is heated, the molecules move _____ and the pressure _____.

When the gas is compressed, the molecules hit the walls more often and the pressure _____.

P3.08 A balloon is inflated by blowing air into it. Explain what would happen if an inflated balloon was put in a freezer.

P3.09 A tin can containing air is tightly sealed so no air can escape. The can is then heated. Describe what happens to:

- **a** the speed of the air molecules inside the can
- **b** how often the air molecules hit the walls of the can
- **c** the force with which the air molecules hit the walls
- **d** the pressure on the walls of the can.

P3.03 Matter and thermal properties

Most substances – solids, liquids and gases – expand when their temperature rises. This is called **thermal expansion**. Thermal expansion happens because the particles gain energy and move faster, pushing each other further apart.

The expansion of solids

Figure P3.09 shows an experiment that demonstrates that a metal ball expands when it is heated.

- When the ball is cold, it just fits through the ring.
- The ball, but not the ring, is heated strongly. It now will not pass through the ring. It has expanded.
- When the ball cools down, it contracts and returns to its original size and will once again pass through the ring.

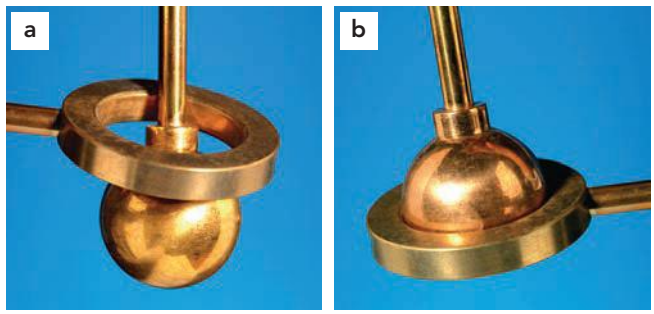

Figure P3.09 a: The metal ball is cold and has passed through the ring. **b:** The metal ball is hot. It has expanded and will no longer fit through the ring.

Uses of expansion

Rivets are used in shipbuilding and other industries to join metal plates. A red-hot rivet is passed through holes in two metal plates and then hammered until the ends are rounded (Figure P3.10). As the rivet cools, it contracts and pulls the two plates together tightly.

A metal lid or cap may stick on a glass jar or bottle, and be hard to unscrew. Heating the lid (for example, by running hot water over it) causes it to expand. The glass expands much less than the metal lid, meaning that the lid loosens and can be removed.

Figure P3.10: Joining two metal plates using a rivet.

KEY WORDS

thermal expansion: the increase in volume of a material when its temperature rises.

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A steel 'tyre' can be fitted on to the wheel of a train while the tyre is very hot. It then cools and contracts, so that it fits tightly on to the wheel (Figure P3.11).

Figure P3.11: Steel tyres are heated so they expand and can be fitted to train wheels. They contract and fit very tightly.

A bimetallic strip (Figure P3.12) is designed to bend as it gets hot. The strip is made of two metals joined firmly together. One metal expands much more than the other. As the strip is heated, this metal expands, causing the strip to bend. The metal that expands more is on the outside of the curve, because the outer curve is longer than the inner one. These strips are used in devices such as fire alarms and thermostats. Thermostats are used to control the temperature of devices such as ovens and irons.

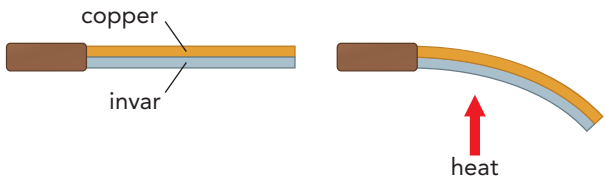

Figure P3.12: A bimetallic strip. Invar is a metal alloy which expands very little when heated. Copper expands more. This difference in expansion causes the strip to bend.

Consequences of expansion

The expansion of materials can cause problems. For example, metal bridges and railway lines expand on hot days, and there is a danger that they might bend. To avoid this, bridges are made in sections, with expansion joints between the sections (Figure P3.13). On a hot day, the bridge expands and the gaps between sections decrease. Railway lines are now usually made from a metal alloy that expands very little. On a concrete roadway, you may notice that the road surface is in short sections. The gaps between are filled with soft tar, which becomes squashed as the road expands.

Figure P3.13: This lorry is about to cross an expansion joint on a road bridge. On a hot day, the bridge expands and the interlocking teeth of the joint move closer together.

The expansion of liquids

Many thermometers use the expansion of a liquid to measure temperature (Figure P3.14). As the temperature of the liquid rises, it expands and the level of liquid in the tube rises.

Figure P3.14: As the temperature drops, so does the volume of the liquid in the thermometer. The alcohol in this thermometer remains liquid at very low temperatures.

Glass containers may crack when hot liquid is placed in them. This is because the inner surface of the glass expands rapidly, before the thermal energy has passed through to the outer surface. The force of expansion cracks the glass. To avoid this, glass such as Pyrex has been developed that expands very little on heating. An alternative is toughened glass, which has been treated with chemicals to reduce the chance of cracking.

The expansion of gases

Gases expand when they are heated, just like solids and liquids. We can explain this using the kinetic model of matter. Figure P3.15 shows some gas in a cylinder fitted with a piston. At first, the gas is cold and its particles press weakly on the piston. When the gas is heated, its particles move faster. Now they push with greater force on the piston and push it upwards. The gas has expanded.

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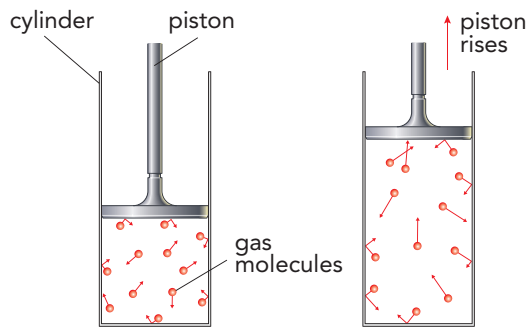

Figure P3.15: A gas expands when it is heated at constant pressure.

The expansion of gases as they heat up means that the density of a hot gas is lower than the density of the same gas when it is cold. This is why hot air rises (Figure P3.16).

Figure P3.16: The expansion of air as it heats up creates thermal currents, which this hang glider is using.

Questions

P3.10 Copy and complete these sentences:

When an object is heated it _____. When it cools it _____.

A bimetallic strip is made of two _____ which expand by different amounts when heated. This causes the strip to _____.

KEY WORDS

melting point: the temperature at which a solid melts to become a liquid.

boiling point: the temperature at which a liquid changes to a gas (at constant pressure).

P3.11 Look at the bridge in Figure P3.17. One end of the bridge is on rollers rather than being fixed. Explain how this helps it cope with extreme temperatures.

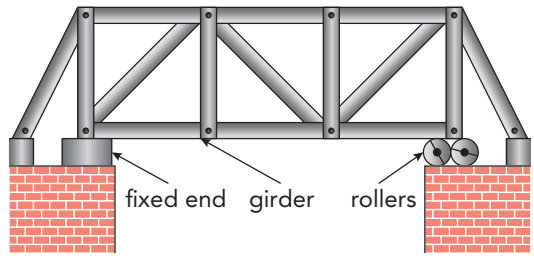

Figure P3.17: A bridge.

P3.12 Figure P3.18 shows an experiment to compare the expansion of liquids. Equal volumes of ethanol, water and mercury were heated in a water bath.

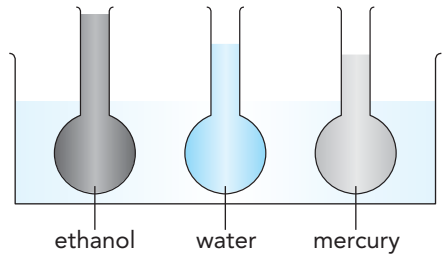

Figure P3.18: Experiment to compare expansion of liquids.

a Which liquid expands the most?

b Explain why this liquid is used in most school laboratory thermometers.

More about changing state

Figure P3.19 shows what happens when you take some ice from the freezer and heat it at a steady rate. In a freezer, ice is at a temperature well below its freezing point, maybe as low as −20 °C. From the graph, you can see that the ice warms up to 0 °C, then stays at this temperature while it melts. The **melting point** of water is 0 °C. When all of the ice has melted, the water's temperature starts to rise again. At 100 °C, the **boiling point** of water, the temperature again remains steady. The water is boiling to form steam. Eventually, all of the water has turned to steam. If you continue to heat the steam, the temperature of the steam will rise again.

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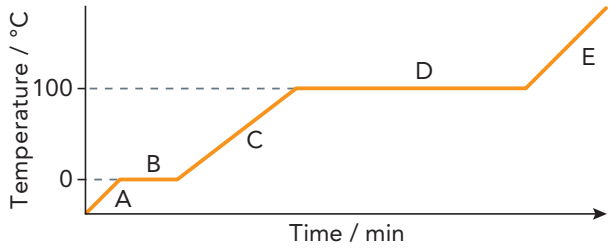

Figure P3.19: A temperature against time graph to show the changes that occur when ice is heated until it eventually becomes steam. **A:** ice is heating up. **B:** ice is melting. **C:** water is heating up. **D:** water is boiling. **E:** steam is heating up.

It takes energy to change a solid into a liquid. The temperature stays the same as the ice melts. Similarly, when a liquid becomes a gas, its temperature stays the same even though energy is being supplied to it. This is due to changes in the chemical potential energy in the bonds between the molecules or atoms. Energy must be provided to break bonds and change a substance from solid to liquid. Energy is also needed to overcome the attraction between the particles when a substance changes from liquid to gas. When these changes are reversed, energy is given out.

The boiling and melting points of a substance change if the air pressure changes. Water has a melting point of 0 °C and a boiling point of 100 °C at standard atmospheric pressure. This is the pressure at sea level, which is about 101.32 kPa or 1 atmosphere. At higher altitudes, water boils at a lower temperature (Figure P3.20).

Figure P3.20: On top of Mount Everest water boils at 71 °C.

Condensation is when a gas changes to a liquid. The particles slow down and they are drawn together. Solidification, or freezing, is when a liquid changes to a solid. As a liquid loses energy, its particles slow down and the bonds holding the particles together re-form. When a substance condenses or solidifies, energy is given out while no temperature change happens. Figure P3.21 shows the temperature of stearic acid as it solidifies.

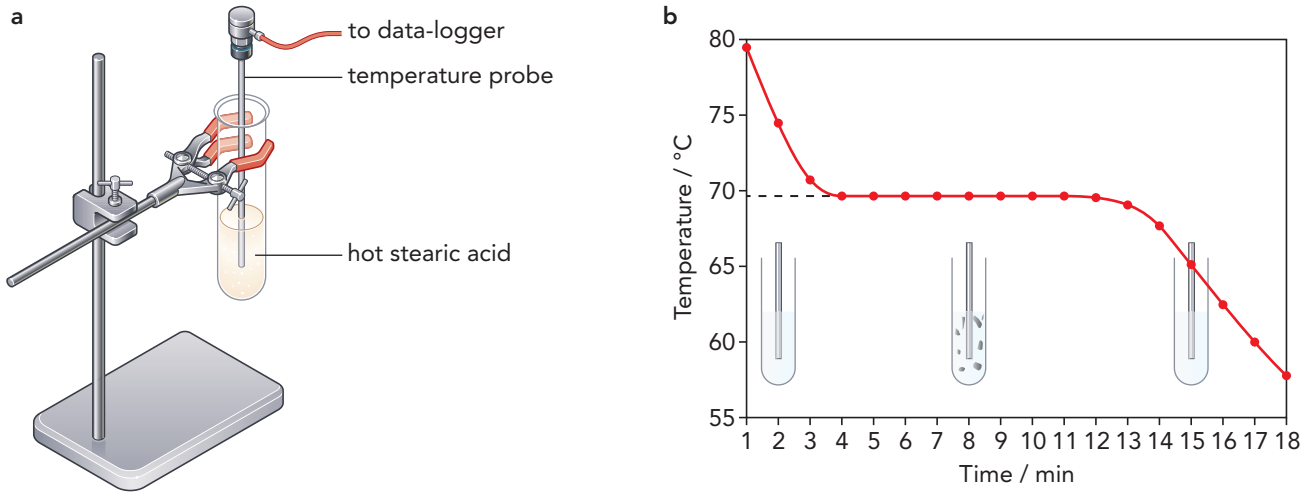

Figure P3.21 a: The thermometer measures the temperature of the wax as it cools. **b:** The graph shows how the temperature changes as the liquid cools to its melting point (70 °C). The temperature remains constant while the liquid solidifies, then the temperature drops again as it cools.

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ACTIVITY P3.02

Breaking free

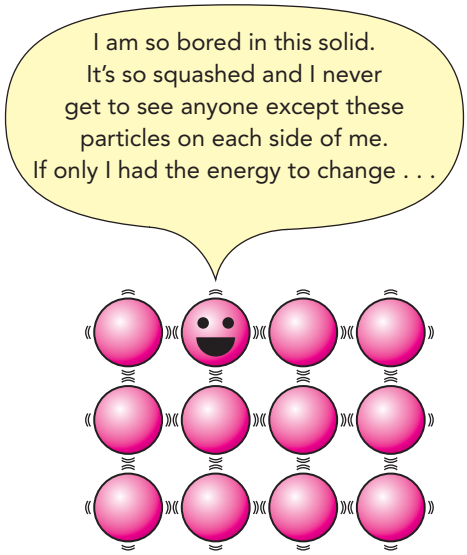

Figure P3.22: Particles in a solid.

Create a comic strip to tell the story of what happens to the particle when it gets what it wants (energy) and changes from a solid to a liquid and then to a gas (Figure P3.22).

Your comic strip should be:

- engaging (use pictures, colour and humour)
- scientifically correct (check back through the chapter so far; use the correct scientific words and explain what is happening).

Peer assessment

Swap comic strips with another group. Study their work and give them feedback. Include:

- three ways it works well
- one suggestion for how it could be even better; this could be something they need to make clearer, or something they could add.

Question

P3.13 Figure 3.19 shows the changes as ice is heated. Sketch and annotate a similar graph to show what will happen to a container of steam placed in a freezer.

Evaporation

A liquid can change state without boiling. After it rains, the puddles dry up even though the temperature is much lower than 100 °C (Figure P3.23). The water from the puddles has evaporated. The liquid water has become a gas called water vapour in the air. This is the process of evaporation. We can think of a vapour as a gas at a temperature below its boiling point.

Figure P3.23: In warm weather puddles evaporate quickly.

A liquid evaporates more quickly as its temperature approaches its boiling point. That is why puddles disappear faster on a hot day than a cold day.

How can we use the kinetic particle model of matter to explain evaporation? Imagine a beaker of water. The water will gradually evaporate. Figure P3.24 shows the particles that make up the water. The particles of the water are moving around, and some are moving faster than others. Some may be moving fast enough to escape from the surface of the water. They become particles of water vapour in the air. In this way, all of the water particles may eventually escape from the beaker, and the water will have evaporated.

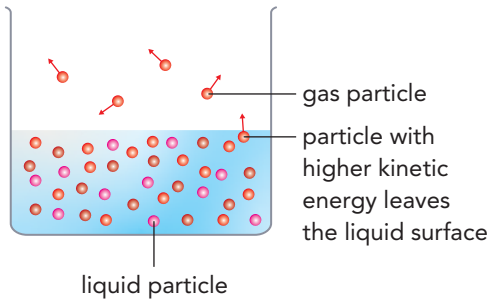

Figure P3.24: Fast-moving particles leave the surface of a liquid. This is how the liquid evaporates.

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If the temperature of the liquid is higher, more of its particles will have enough energy to escape. This means the liquid will evaporate more quickly. The hottest particles are most likely to escape as they have most energy. When they escape, the average energy of the remaining particles is less, so the liquid cools down.

Cooling by evaporation

If you get wet, perhaps in the rain or after swimming, you will notice that you can quickly get cold. The water on your body is evaporating, and this cools you down. Why does evaporation make things cooler?

Look again at Figure P3.24. The particles that are escaping from the water are the fastest-moving ones. They are the particles with the most kinetic energy. This means that the particles that remain are those with less energy. Now the particles of the liquid have less energy (on average) and so the temperature of the water decreases. The water cools down.

Speeding up evaporation

We can use the kinetic model to explain some ways of speeding up evaporation. Table P3.04 shows the factors which affect the rate of evaporation.

How is evaporation different from boiling?

Boiling and evaporation both involve a liquid turning into a gas. Table P3.05 describes the differences between the two processes.

Boiling	Evaporation
only occurs at the boiling point – 100 °C for water	occurs at any temperature
happens throughout the liquid – you can see bubbles throughout a boiling liquid	only occurs at the surface of the liquid
energy is required to overcome attractive forces	no energy is required – the most energetic particles escape, lowering the temperature of the remaining liquid

Table P3.05: differences between boiling and evaporation.

Questions

P3.14 Copy and complete the following sentences.

a _____ is the change from a liquid to a gas at a temperature below the boiling point.

b Evaporation causes a liquid to cool because the _____ moving, hotter particles are the most likely to escape. This means the particles left behind are the slower moving, _____ ones.

P3.15 Use the kinetic particle model to explain why a wet towel will dry much faster if hung outside on a warm, windy day than if left folded up in a bag.

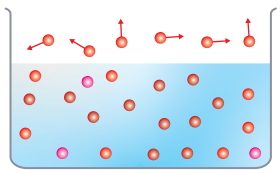
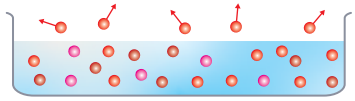
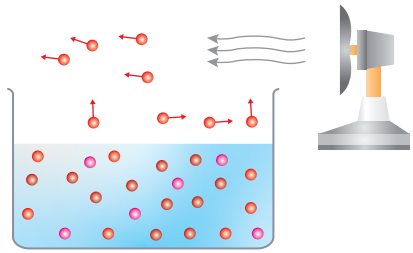
Increasing the temperature	Increasing the surface area	Blowing air across the surface
		
Increasing the temperature of the liquid means that, on average, the particles have more kinetic energy. More of the particles will have enough energy to escape. This means the liquid will evaporate more quickly.	If the liquid has a greater surface area, more of the particles are close to the surface, and so they can escape more easily. This means the liquid evaporates more quickly.	A draught is moving air. When particles escape from the water, they are blown away so that they cannot fall back into the water. This helps the liquid evaporate quickly. As a liquid evaporates, the remaining liquid cools.

Table P3.04: Methods of speeding up evaporation.

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P3.04 Thermal processes

Thermal energy transfers from a hotter place to a colder place, that is, from a higher temperature to a lower temperature. Thermal energy requires a temperature difference if it is to be transferred. We will now look at the three ways in which thermal energy is transferred: conduction, convection and radiation.

Conduction

If you touch a wooden spoon and a metal spoon, both at room temperature, the metal spoon feels colder than the wooden spoon. How can this be?

The reason is **thermal conduction**. When your finger touches a metal object, thermal energy flows out of your finger and into the metal. Metal is a good **thermal conductor**, so thermal energy spreads rapidly through the metal. Thermal energy continues to escape from your finger, leaving it colder than before. The temperature-sensitive nerves in your fingertip tell your brain that your finger is cold. So, you think you are touching something cold.

When you touch a wooden object, thermal energy conducts into the area that your finger is in direct contact with. However, because wood is a good **thermal insulator**, the thermal energy travels no further. Your finger loses no more thermal energy and remains warm. The message from the nerves in your fingertip is that your finger is warm. So, you think you are touching something warm.

Comparing conductors and insulators

We can compare how well materials conduct by touch, but Figure P3.25 shows a better method. Rods of different materials have paper clips attached at one end using petroleum jelly. The other ends of the rods are heated. If the material is a good thermal conductor, heat will quickly reach the petroleum jelly. This will cause the jelly to melt and the paper clip will fall.

Figure P3.26 compares conductors and insulators. In general, metals are good conductors of thermal energy and non-metals are poor conductors. Air and water are very poor conductors of thermal energy.

KEY WORDS

thermal conduction: the transfer of thermal energy by the vibration of molecules.

thermal conductor: a substance that conducts thermal energy.

thermal insulator: a substance that conducts very little thermal energy.

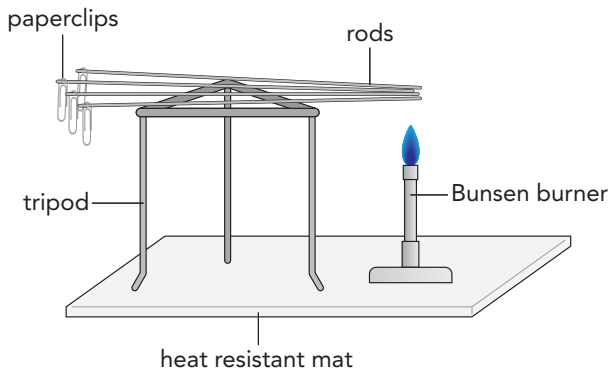

Figure P3.25: An experiment to compare thermal conductors.

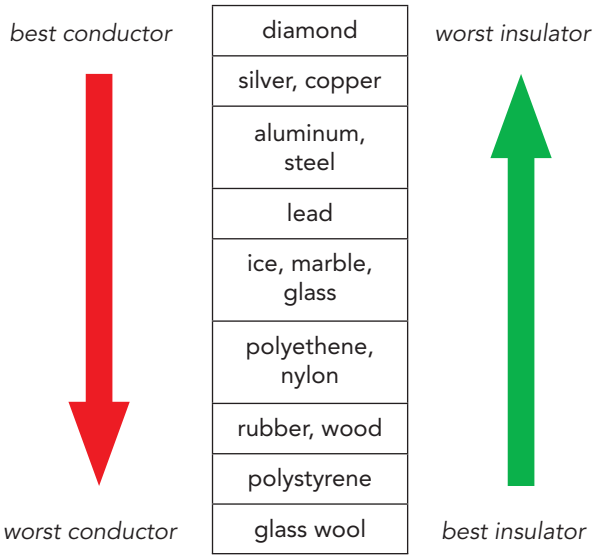

Figure P3.26: Comparing conductors of thermal energy, from the best conductors to the worst. A bad conductor is a good insulator. Almost all good conductors are metals; polymers (plastics) are at the bottom of the list. Glass wool is an excellent insulator because it is mostly air.

Explaining conduction in metals and non-metals

Both metals and non-metals conduct thermal energy. Metals are generally much better conductors than non-metals. We need different explanations of conduction for these two types of material.

We will start with non-metals. Imagine a long glass rod (Figure P3.27). One end is being heated, the other end is cold. This makes a temperature difference between the two ends, and so thermal energy flows along the rod. What is going on inside the rod?

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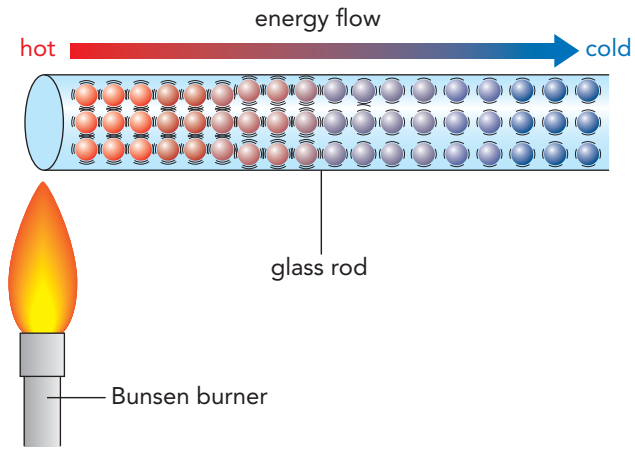

Figure P3.27: Conduction of thermal energy in non-metals. A glass rod is heated at one end. Thermal energy travels from the hot end to the cold end.

Look at the particles inside the rod in Figure P3.27. At the hot end of the rod, the atoms are vibrating much more than they are at the cold end. As the atoms vibrate, they collide with their neighbours. This process results in each atom sharing its energy with its neighbouring atoms. Atoms with a lot of energy end up with less, and those with a little end up with more. The collisions gradually transfer energy from the atoms at the hot end to those at the cold end. Energy is steadily transferred down the rod, from the hot end to the cold end.

This is how poor conductors (such as glass, ice and plastic) conduct thermal energy. It is not a very efficient method of thermal energy transfer.

Metals are good conductors for another reason. Many of the **electrons** in metallic conductors are free to move (they are **delocalised (mobile) electrons**). These are the particles which carry electric current. They also carry thermal energy as they get hot and move through the metal. Figure P3.28 shows a copper rod, heated in the same way as the glass rod. Notice the free electrons, which carry thermal energy through the metal.

Liquids can also conduct thermal energy, because the particles of which they are made are in close contact with one another. However, as the particles are free to move, vibrations are not passed on as easily as in a solid.

KEY WORDS

electron: a negatively charged particle, smaller than an atom.

delocalised (mobile) electrons: electrons which are not attached to an atom.

The particles in gases are very spread out, making gases very poor conductors of thermal energy.

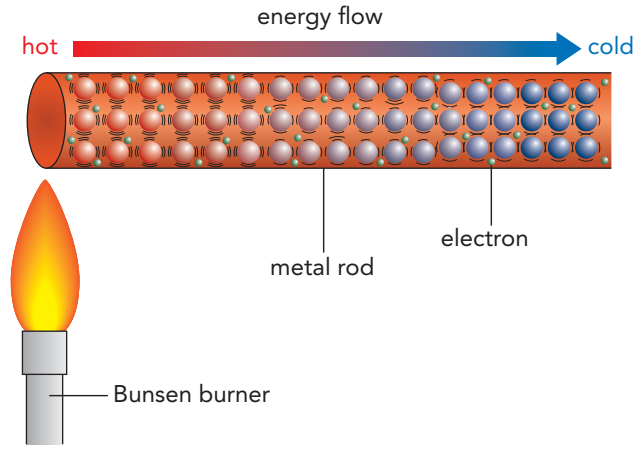

Figure P3.28: Conduction of thermal energy in metals. Metals have free electrons which carry thermal energy, making metals good conductors.

Questions

P3.16 Copy these sentences and choose the correct word.

Conduction happens mostly in **solids / liquids / gases**. Thermal energy flows from the **hotter / cooler** parts of an object to the **hotter / cooler** parts. A material which does not conduct thermal energy well is called **a conductor / an insulator / a resistor**. An example is **copper / polystyrene / gold**.

P3.17 Explain why it is better to use a wooden spoon to stir hot soup than a metal spoon.

P3.18 Use the information in Figure P3.26 to explain why walking on a marble floor in bare feet would feel colder than walking on a wooden floor.

P3.19 Explain why two thin layers of clothing are often warmer than one thick layer.

P3.20 Explain why:

a copper is a better conductor than wood

b wood is a better conductor than air.

Convection

As we have seen, liquids and gases are not usually good conductors of thermal energy. Thermal energy transfer in liquids and gases is mainly by another method, known as convection.

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Figure P3.29: The heater is heating the air going into the balloon. This makes the air expand so it becomes lighter and makes the balloon float up.

When air is heated, it expands and becomes lighter, so it floats upwards (Figure P3.29).

The opposite effect can be seen in Figure P3.30. Cold air sinks. This photo is taken with a technique which shows the flow of air. You can see cold air sinking down below the frozen pizza.

Figure P3.30: Cold air sinks below any object which is colder than its surroundings.

The rising of hot air is just one example of **convection**. Hot air can rise because air is a **fluid**, and convection can be observed in any fluid (any liquid or gas). Convection does not happen in solids because the particles are in fixed positions so they cannot flow.

Figure P3.31 shows how a convection current can be observed in water. Above the flame, water is heated and expands, so it floats upwards. The purple dye shows how it moves. Colder, heavier water flows in to replace it.

A **convection current** is a movement of a fluid that carries energy from a warmer place to a cooler one. This highlights an important difference between convection and conduction.

- In convection, energy is transferred through a material from a warmer place to a cooler place by the movement of the material itself.
- In conduction, energy is transferred through a material from a warmer place to a cooler place without the material itself moving.

Figure P3.31: Because water is clear and colourless, it can be difficult to see how the water moves to form a convection current. Crystals of potassium manganate(VII) act as a purple dye to show the movement of the water.

KEY WORDS

convection: the transfer of thermal energy through a material by the movement of the material itself.

fluid: a substance which can flow; liquids and gases are fluids.

convection current: the transfer of thermal energy by the motion of a fluid.

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Convection currents at work

Convection currents help to share energy between warm and cold places. If you are sitting in a room with an electric heater, thermal energy will be moving around the room from the heater as a result of convection currents, which rise from the heater (Figure P3.32). You are likely to be the source of convection currents yourself, since your body is usually warmer than your surroundings. Many biting insects make use of this effect. For example, bed bugs crawl across the bedroom ceiling. They can detect a sleeping person below by finding the warmest spot on the ceiling. Then they drop straight down on to the sleeper. This is a lot easier than crawling about on top of the bedding.

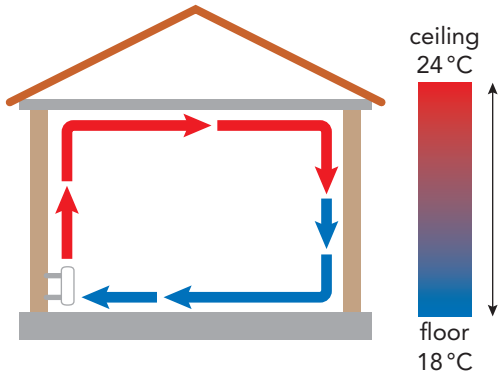

Figure P3.32: Convection currents rise above the warm objects in a room.

Cold objects also produce convection currents. You may have noticed cold water sinking below an ice cube in a drink. In a refrigerator, the freezing surface is usually positioned at the top and the back, so that cold air will sink to the bottom. Warm air rises to replace the cold air as it sinks. The warm air is then cooled (see Figure P3.33).

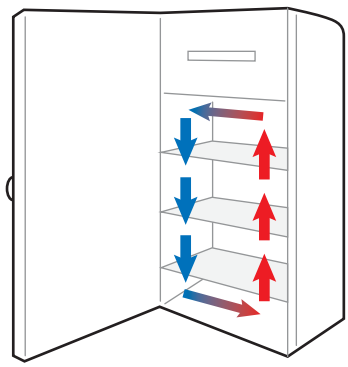

Figure P3.33: In a refrigerator, cold air sinks from the freezing compartment. If the freezer was at the bottom, cold air would remain there, and the food at the top would not be cooled.

Explaining convection

We have already seen that convection results from the expansion of a fluid when it is heated. Expansion means an increase in volume while mass stays constant. This means that density decreases. A less dense material is lighter and so is pushed upwards by the surrounding denser material.

The particles in the hotter fluid have more kinetic energy so they move around faster. As they flow from place to place, they take this energy with them.

Convection is the main method of thermal energy transfer in fluids. Thermal energy can be conducted through a liquid, but this is generally a slow process compared with convection.

Questions

P3.21 Copy this picture of a pan of water (Figure P3.34). Add arrows labelled 'cold water' and 'hot water' to show the convection current in the pan.

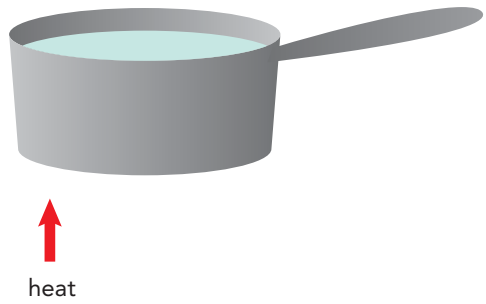

Figure P3.34: Heating a pan of water.

P3.22 Look at Figure P3.35. The ice cube in this glass floats at the top of the water. Draw and label a diagram to show how the ice cube creates a convection current which cools all of the water.

Figure P3.35: Cooling a drink by adding ice.

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P3.23 An inventor makes an electric kettle with the heating element at the top. Explain why it will not work.

P3.24 **a** Draw diagrams to show the difference in the arrangement of particles in a hot gas and a cold gas.

b Use your diagrams to explain why hot gases rise. Use the words 'expand' and 'density' in your answer.

Radiation

The light that reaches us from the Sun and other stars travels to us through space in the form of electromagnetic radiation. This radiation travels as electromagnetic waves. It travels over vast distances, following a straight line through empty space. Radiation is the only form of thermal energy transfer which does not involve the movement of particles. Thermal radiation does not need a medium to travel through. It can travel through a vacuum. Infrared radiation is part of the **electromagnetic spectrum** – a range of radiation including light, X-rays and ultraviolet radiation.

All objects emit **infrared radiation**. The hotter an object, the more infrared radiation it gives out. You can use this idea to help you to do a bit of detective work. Imagine you arrive at a crime scene. The suspect says he has just arrived by car. You suspect he has been at the scene for an hour, giving him time to commit the crime. Holding your hand over the engine compartment will quickly tell you if the engine is radiating thermal energy.

Our skin detects the infrared radiation produced by a hot object. Nerve cells just below the surface respond to thermal energy. You notice this if you are outdoors on a sunny day.

To summarise, infrared radiation:

- is produced by warm or hot objects
- is a form of electromagnetic radiation
- travels through empty space (and through air) in the form of waves
- travels in straight lines
- warms the object that absorbs it
- is invisible to the naked eye
- can be detected by nerve cells in the skin.

Figure P3.36 shows another way of detecting infrared radiation: by using a temperature-sensitive camera. The photograph of a woman sitting at a desk is taken with a camera which detects infrared radiation instead of light. It is very sensitive to slight differences in temperature.

KEY WORDS

electromagnetic spectrum: a range of electromagnetic waves with different wavelengths, which travel at the same speed (the speed of light) and can travel through a vacuum.

infrared radiation: electromagnetic radiation with a wavelength greater than that of visible light; sometimes known as thermal energy radiation.

Figure P3.36: Using an infrared-sensitive camera. Slight variations in temperature show up as different colours. The scale shows how the colour relates to temperature.

Questions

P3.25 Which statement about infrared radiation is true?

A Infrared radiation travels slower than light.

B Infrared radiation cannot be reflected.

C Infrared radiation can travel through a vacuum.

D Infrared radiation is transferred by the movement of particles.

P3.26 Explain why thermal energy from the Sun can only reach us by radiation, not conduction or convection.

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P3.27 What evidence is there in this infrared photograph (Figure P3.37) to suggest that the car has only just broken down?

Figure P3.37: Infrared photograph of a car.

ACTIVITY P3.03

Thermal imaging

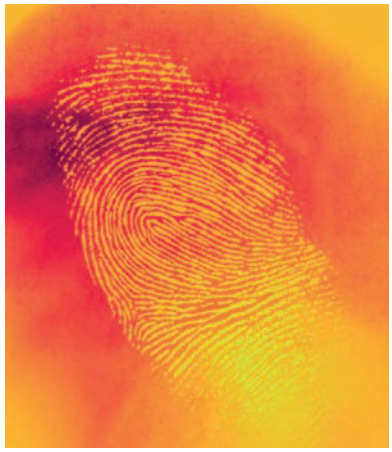

Figure P3.38: Thermal image of a fingerprint.

A science museum is preparing a display about infrared photography (Figure P3.38). You are a researcher and have been given the following brief.

Investigate one of the uses of this technology and prepare an information board about it. Your board should be one side of A4 paper. It must include at least one eye-catching picture taken with an infrared camera, and a maximum of 150 words describing the science and how it is used.

The board should be interesting to the general public and also detailed enough to be relevant to high school physics students.

CONTINUED

Uses of infrared technology include:

- medicine
- military
- detection of drug farms
- astronomy
- wildlife photography
- forensic science
- studying thermal energy loss from buildings.

Peer assessment

Display each group's work from Activity P3.03 around the classroom. Take a class vote on which board best meets the brief. Discuss what makes it a good piece of work. Adapt your board to add some of the features you identified.

Good absorbers, good emitters

On a hot, sunny day, car drivers may park their cars with a sunshield behind the windscreen (Figure P3.39). A sunshield is usually shiny, because this reflects light and infrared radiation from the Sun. This stops the car getting uncomfortably hot. The black plastic parts of the car (such as the steering wheel and dashboard) are very good absorbers of infrared radiation, and they can become too hot to touch.

Figure P3.39: A sunshield reflects unwanted radiation, which would otherwise make the car very hot.

It is the surface that determines whether an object absorbs or reflects infrared radiation. A surface that is a good reflector is a poor absorber. On a hot day, you may have noticed how the black surface of a tarred (metalled) road emits thermal energy. Black surfaces readily absorb infrared radiation. They are also good emitters.

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You may also have noticed that you stay cooler on a hot day if you wear light coloured clothes. Light surfaces do not absorb much thermal radiation. Instead, they reflect the radiation. The house in Figure P3.40 is painted white to reflect infrared radiation.

Figure P3.40: This house is built from bottles filled with sand. It is painted white to reduce absorption of infrared radiation.

- Shiny or white surfaces are the best reflectors (the worst absorbers and emitters).
- Matte black surfaces are the best absorbers and emitters (the worst reflectors).

Questions

P3.28 Why is the worker in Figure P3.41 wearing a shiny suit?

Figure P3.41: A worker supervising the flow of hot molten metal.

P3.29 Which will stay hot longer: tea in a shiny silver teapot or tea in a dark brown one? Explain your answer.

Factors affecting infrared radiation

All objects emit radiation and absorb radiation from their surroundings. The hotter an object is, the more radiation it emits each second, or the more power it radiates. Any object which is hotter than its surroundings radiates more energy per second than it absorbs. Therefore, it will cool down. An object which is cooler than its surroundings absorbs more energy per second than it radiates until it reaches the temperature of its surroundings. An object with a temperature that remains constant absorbs thermal energy at the same rate as it emits thermal energy. An object with a large surface area emits thermal energy at a faster rate.

Figure P3.42 shows three beakers of water. The room temperature is 20 °C. All three beakers radiate and absorb energy, but the amount of radiation and absorption depends on the temperature.

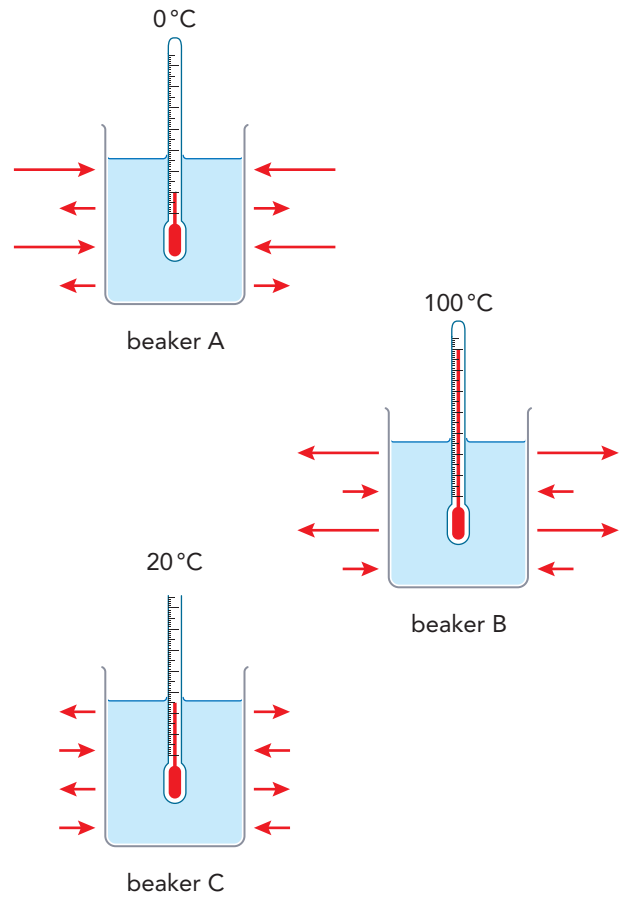

Figure P3.42: Beaker A will warm up, beaker B will cool down and beaker C will remain at a constant temperature.

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EXPERIMENTAL SKILLS P3.01

Investigating the emission and absorption of infrared radiation

In this investigation you will use cans of water with different surfaces to investigate which emits most infrared radiation and which absorbs most infrared radiation.

The amount of infrared radiation emitted also depends on the surface area and temperature of the objects, so these must be controlled in your experiment.

You will need:

- 1 shiny silver can and 1 dull black can
- 2 lids with holes for thermometers
- 2 thermometers or electronic temperature probes
- timer
- kettle
- board to isolate the cans from each other
- Bunsen burner or electrical heater.

Safety

Take care when using hot water. Do not touch or move the cans while they are full of very hot water. Wear eye protection when using a Bunsen burner.

Getting started

Look at Figure P3.43. Use what you know about thermal energy transfers to explain why the cans must be fitted with lids, and why they should stand on a wooden or plastic surface.

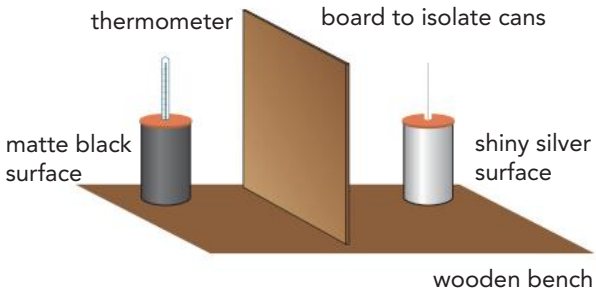

Figure P3.43: Set-up for the experiment.

Experiment A: Which surface radiates better, black or shiny?

Method

1 Set up the experiment as shown in Figure P3.43.
2 Fill the two cans with equal volumes of *hot* water.
3 Use thermometers or electronic temperature probes to measure the temperature of the water in each can every minute for ten minutes.

Questions

1 What features of the experimental design ensure that this is a fair test?
2 Plot a graph of *temperature* on the *y*-axis against *time* on the *x*-axis. Plot both sets of results on the same graph.
3 What can you conclude from your results?

Experiment B: Which surface absorbs thermal energy better, black or shiny?

Method

1 Set up the experiment as shown in Figure P3.44; use the same cans as in experiment A.
2 Fill the cans with equal volumes of *cold* water.
3 Place the cans at equal distances from the Bunsen flame or electric heater.
4 Use thermometers or electronic temperature probes to measure the temperature of the water in each can every minute for ten minutes.

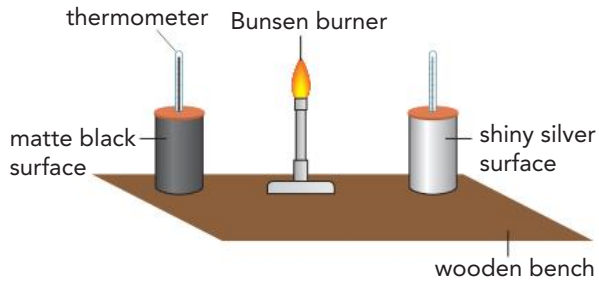

Figure P3.44: Set-up for the experiment.

Questions

1 Plot a similar graph to experiment A.
2 What can you conclude from your results?

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Applications and consequences of thermal energy transfer

In this topic, we will see how we can use ideas about thermal energy transfers to understand a lot of different situations. Remember that:

- Thermal energy travels from a hotter place to a colder place. It is the temperature difference that makes it flow.
- Conduction is the main way in which energy can pass through a solid. Energy travels through the solid but the solid itself cannot move.
- Convection is the main way in which energy is transferred in a fluid. Warm fluid moves around, carrying energy with it.
- Radiation is the only way in which thermal energy can travel through empty space. Infrared radiation can also pass through some transparent materials such as air.

Hot objects have a lot of internal energy. As we have seen, energy tends to escape from a hot object, spreading to its cooler surroundings by conduction, convection and radiation. This can be a great problem. We may use a lot of energy (and money) to heat our homes during cold weather, and the energy simply escapes. We eat food to supply the energy we need to keep our bodies warm, but energy escapes from us at a rate of about 100 watts (100 W = 100 J/s).

To keep energy in something that is hotter than its surroundings, we need to insulate it. Knowing about conduction, convection and radiation can help us to design effective insulation.

Remember that all three mechanisms of energy transfer (conduction, convection and radiation) may be involved when an object warms up or cools down.

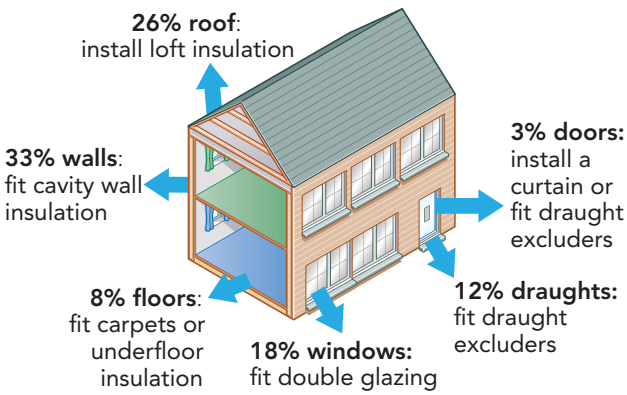

Figure P3.45: Insulating a house reduces thermal energy loss and heating costs.

Home insulation

A well-insulated house can avoid a lot of energy wastage during cold weather. Insulation can also help to prevent the house from becoming uncomfortably hot during warm weather. Figure P3.45 shows where thermal energy is lost from a house, and some ways to reduce thermal energy losses. More details are listed in Table P3.06.

Method	Why it works
 thick curtains, draught excluders	stops convection currents, and so prevents thermal energy transfer
 loft and underfloor insulating materials	prevents conduction of thermal energy through floors and ceilings
 double and triple glazing of windows	vacuum between glass panes cuts out losses or gains by conduction and convection
 cavity walls	reduces thermal energy loss or gain by conduction
 foam or rockwool in wall cavity	further reduces thermal energy transfer by convection

Table P3.06: Methods of retaining energy in a house in a cold climate, and of keeping a house cool in a hot climate.

Double-glazed windows usually have a vacuum between the two panes of glass. This means that energy can only escape by radiation, since conduction and convection both require a material. Modern houses are often built with cavity walls, with an air gap between the two layers of bricks.

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It is impossible to have a vacuum in the cavity, and convection currents can transfer energy across the gap (see Figure P3.46a). Filling the cavity with foam means that a small amount of energy is lost by conduction, although the foam is a very poor conductor. However, this does stop convection currents from flowing (Figure P3.46b), so there is an overall benefit.

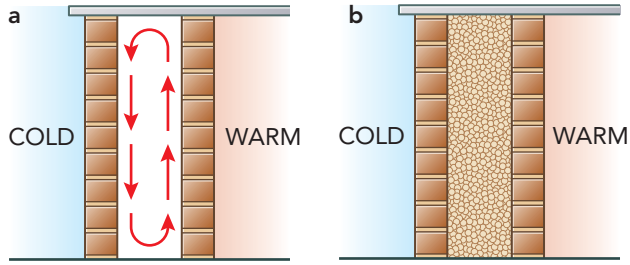

Figure P3.46 a: A cavity wall reduces thermal energy loss by conduction because air is a good insulator. However, a convection current can transfer energy from the inner wall to the outer wall. **b:** Filling the cavity with foam or mineral (glass or rock) wool prevents convection currents from forming.

Vacuum flasks

Vacuum flasks are used to keep hot drinks hot. They can also be used to keep cold drinks cold. Giant vacuum flasks are used to store liquid nitrogen and helium at very low temperatures, ready for use in such applications as body scanners in hospitals. They also have medical uses, such as for storing frozen embryos for IVF treatment (Figure P3.47).

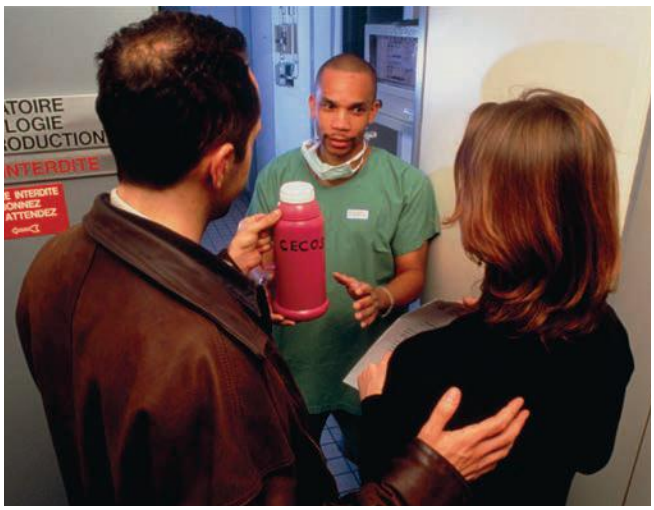

Figure P3.47: This couple are hoping to have a baby by IVF. The flask they are holding contains their frozen embryos.

Figure P3.48 shows the construction of a vacuum flask. Glass is generally used, because glass is a good insulator. However, some flasks are made of steel for added strength. Air is removed from the gap between the double walls, creating a vacuum. This reduces losses by conduction and convection because both of them need a material to travel through. The silver coating on the glass reduces losses by radiation by reflecting any infrared radiation. The stopper is made of plastic and it prevents losses by convection and evaporation.

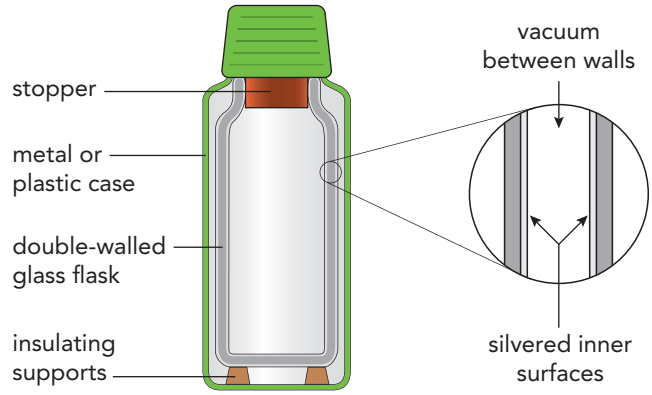

Figure P3.48: A vacuum flask is cleverly designed to keep hot things hot by reducing thermal energy losses. It also keeps cold things cold. Although we might say 'it stops the cold getting out', it is more correct to say that it prevents thermal energy from getting in. The first such flask was designed by James Dewar, a Scottish physicist, in the 1870s. He needed flasks to store liquefied air and other gases at temperatures as low as −200 °C. Soon after, people realised that a flask like this was also useful for taking hot or cold drinks on a picnic.

Campfires

Wood burns on a bonfire to produce thermal energy. The heating effect you experience when sitting by a fire is almost entirely due to radiation (see Figure P3.49). Air is a bad conductor and thermal energy transfer due to convection will heat the air above the fire.

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Figure P3.49: The older child will feel hotter than the younger child as his black T-shirt absorbs infrared radiation, whereas the white T-shirt reflects the infrared radiation.

ACTIVITY P3.04

Marketing a vacuum flask

Imagine you have just invented the vacuum flask. You want to go into business producing and selling flasks but you need finance. Prepare a presentation for potential investors. You will need to explain the technical details of how it works. You must use the words 'conduction', 'convection' and 'radiation'. The investors want to know you are an expert and understand the science. You should also explain why your product will be popular with customers.

Your presentation can include an information leaflet, a video or an advertising poster.

Climate

Radiation from the Sun is essential for life on Earth. The Sun's radiation warms the Earth. The warm Earth emits some infrared radiation. Gases in the Earth's atmosphere, such as carbon dioxide, absorb some of this thermal energy and this warms our atmosphere. This is the greenhouse effect (Figure P3.50) and without it, life on Earth would be impossible. However, the amount of greenhouse gases in the atmosphere is increasing, trapping more thermal energy. This means that Earth and its atmosphere are absorbing more infrared radiation than they emit. This is the cause of global warming.

REFLECTION

How easy do you find it to identify the type of thermal energy transfer in a situation?

Think about questions you can ask to identify whether it is conduction, convection or radiation; for example: can this transfer happen in space? If yes, then it must be radiation.

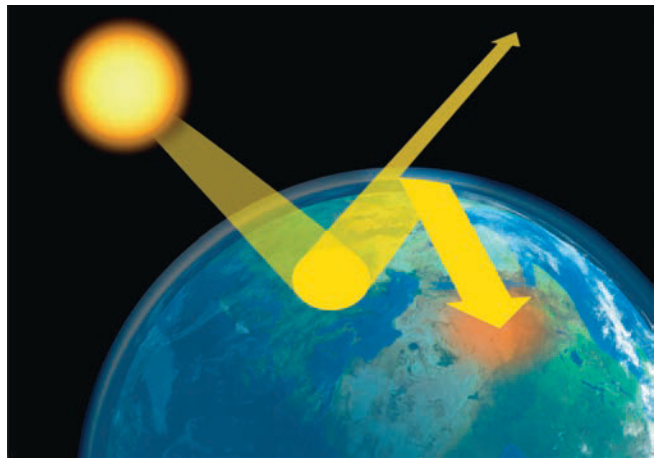

Figure P3.50: For the Earth to maintain a constant temperature, infrared radiation must be emitted at the same rate as it is absorbed. Upsetting this balance is causing global warming.

Questions

P3.30 In a rolling mill, iron is heated to make it malleable and it is then passed through rollers to produce thin sheets of the metal. Explain how the following become hot in this process:

- **a** the rollers which press the metal
- **b** the face of a worker
- **c** the air in the building.

P3.31 Figure P3.51 shows a solar water heater. Cold water flows through the pipes and is heated by the Sun.

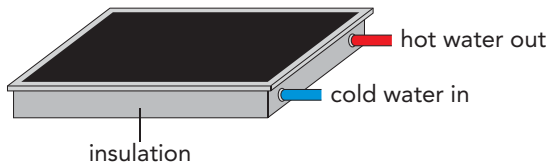

Figure P3.51: A solar water heater.

Suggest reasons why:

- **a** the inside of the panel is painted black
- **b** the back of the panel is insulated
- **c** the cold water enters at the bottom of the panel, and leaves at the top.

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PROJECT P3.01 MAKING A GAME

Your task is to make a game to check how well you have understood this topic (Figure P3.52). You can invent your own game or use one of the ideas below.

Pairs

Make pairs of cards, one with a key word and the other with its definition. Do this for as many key words or ideas as you can find. Be creative – for example, you could draw Brownian motion rather than write a definition.

Put all the cards face down on a table, making sure they are mixed up.

Players take turns to turn over two cards. If they match, the player keeps them and takes another go. If they do not match, the player turns them face down again and the next player takes a turn.

The winner is the player with most cards at the end.

Banned words

In this game a player takes a card which has a key word on it and a list of banned words.

An example is shown here.

The player has to describe the word 'evaporation' to their team without using any of the banned words. They could say, 'it is the change of state that happens when water turns to water vapour'.

Evaporation

- liquid
- gas
- heat
- particle

You can make your game harder or easier by the words you choose for your banned list.

Make a set of cards for the following words and phrases: solid, liquid, gas, evaporation, kinetic model of matter, Brownian motion, temperature, expand, change of state, conduction, convection, radiation.

When you have made your cards, swap with another group and play the game. Players take turns choosing a card and describing the word to their team. The aim is to get through all the cards as quickly as possible.

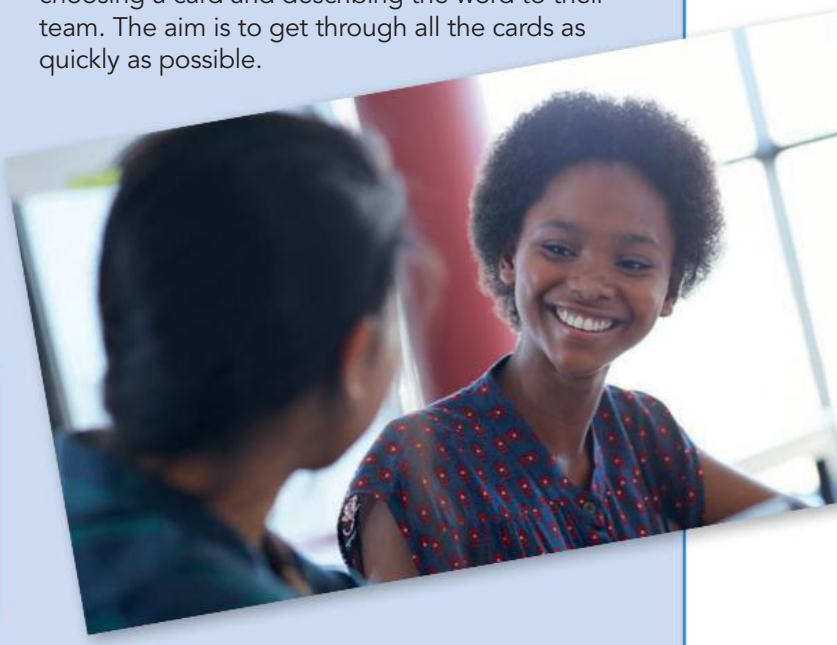

Figure P3.52: Playing games can help you to remember important facts and ideas.

SUMMARY

Matter can exist in three states: solid, liquid and gas.
Solids have a fixed shape and volume. Liquids have a fixed volume but take the shape of their container. Gases expand to fill their container.
The kinetic particle model explains the behaviour of materials by describing what is happening to the particles of which they are made.
According to the kinetic model, matter is made of moving particles that are close together in solids and liquids, and far apart in gases.

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CONTINUED

There are attractive forces between particles that act strongly when the particles are close together.
In Brownian motion, the movement of water or air particles is revealed by their effect on visible grains of pollen or smoke particles.
As the temperature of a substance increases, the kinetic energy of its particles increases.
The particles of a gas bombard the walls of its container. This causes pressure. Increasing temperature increases pressure. Decreasing the volume increases the pressure.
Solids, liquids and gases expand when their temperatures rise, and contract when the temperature drops.
Expansion can cause problems such as the bending of train tracks, but can also be useful, for example in thermometers.
When a liquid evaporates the most energetic particles escape from the surface, so the liquid cools.
Evaporation occurs at temperatures below the boiling point of the liquid. It happens faster at higher temperatures, with a larger surface area or if there is a draught across the surface.
Metals are good thermal conductors. Most non-metals are good insulators.
Metals are good thermal conductors because they have free electrons.
Hot fluids rise, cold fluids sink. This causes convection currents.
Hot fluids rise because they are less dense than cold fluids.
Infrared radiation transfers thermal energy using electromagnetic waves.
Infrared radiation does not require a medium (it can travel through a vacuum).
Shiny, white surfaces reflect infrared radiation. They are poor emitters and absorbers of infrared radiation.
Dull, black surfaces are good absorbers and emitters of infrared radiation, but poor reflectors.

PRACTICE QUESTIONS

1 **Identify** which *one* of these statements is describing a gas.

A It expands to fill the volume of its container.

B It has a fixed size and shape.

C It has a fixed volume but takes up the shape of its container.

D It has strong forces between the particles. **[1]**

2 Identify the word which describes a material that does not let thermal energy pass through it.

A conductor **B** vacuum **C** resistor **D** insulator **[1]**

3 **Give** the *two* states of matter in which convection can happen. **[2]**

COMMAND WORD

identify: name/select/recognise.

COMMAND WORD

give: produce an answer from a given source or recall/memory.

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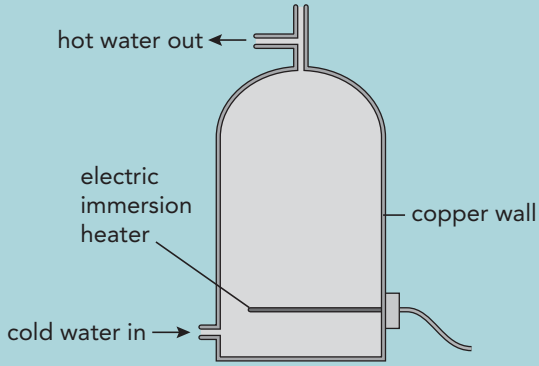
CONTINUED

4 **Explain** why hot fluids rise and cold fluids sink. **[3]**

5 **Describe** the differences between solids, liquids and gases in terms of the arrangement and movement of their particles. **[6]**

6 This diagram shows an electric water heater.



a The copper wall is hot to touch. Give the name of the process by which thermal energy from the water passes through the wall. **[1]**

b Describe how a heater at the bottom of the tank heats all the water in the tank. **[3]**

c The hot walls transfer thermal energy to the surroundings. **Suggest** a way this thermal energy loss could be reduced. **[1]**

[Total: 5]

7 A student observes smoke particles under a microscope. The smoke is lit up so she sees the smoke particles as dots of light.

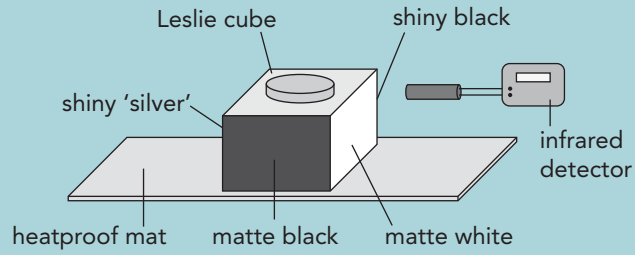
a Describe the movement of the smoke particles. **[1]**

b Give the name of the particles which are causing this movement. **[1]**

c Explain why observation of this movement provides evidence for the kinetic particle model of matter. **[2]**

[Total: 4]

8 The diagram shows a Leslie cube. It is a metal box and each side has a different surface.



Saraya uses a Leslie cube to investigate infrared radiation. She fills the cube with boiling water so all sides are at the same temperature. She uses the infrared detector to investigate the radiation from each surface.

COMMAND WORDS

explain: set out purposes or reasons/make the relationships between things clear/say why and/or how and support with relevant evidence.

describe: state the points of a topic/give characteristics and main features.

COMMAND WORD

suggest: apply knowledge and understanding to situations where there is a range of valid responses in order to make proposals/put forward considerations.

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CONTINUED

a **State** why it is important to keep the detector the same distance from each side. **[1]**

b The temperature of the shiny black side is 65.3 °C.

Deduce the temperatures of the other three sides.

Choose from this list:

64.5 °C 71.2 °C 60.4 °C

matte black: _____

matte white: _____

shiny silver: _____ **[3]**

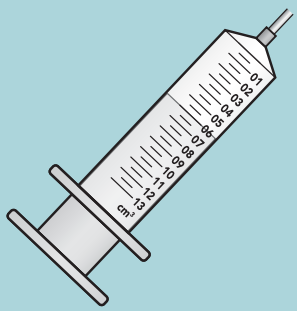
c Saraya's infrared detector gave the temperature to the nearest 0.1 °C.

Zain repeats the experiment using a different infrared detector which gives the temperature to the nearest degree.

Consider how Zain's conclusion will differ from Saraya's. **[1]**

[Total: 5]

9 The diagram shows a syringe containing a small amount of air. The end of the syringe is sealed so no air can enter or leave.



a **Determine** the amount of air in the syringe from the diagram. **[1]**

b A student pushes in the end of the syringe, compressing the gas.

State and explain what happens to the pressure of the air. **[2]**

c The syringe is placed on a radiator. After a while, the student notices that the volume of the air has increased.

Explain, in terms of air molecules, why the volume of air increased. **[2]**

[Total: 5]

COMMAND WORDS

state: express in clear terms.

deduce: conclude from available information.

COMMAND WORD

consider: review and respond to given information.

COMMAND WORD

determine: establish an answer using the information available.

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SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
describe the distinguishing properties of solids, liquids and gases	P3.01			
describe the structure of solids, liquids and gases in terms of the movement and separation of particles	P3.01			
describe the structure of solids, liquids and gases in terms of the forces and distances between particles	P3.01			
use kinetic theory to describe how the temperature of a gas is linked to the movement of its particles	P3.01			
describe Brownian motion and explain how it provides evidence for the kinetic theory	P3.01			
state that evaporation causes cooling	P3.01			
describe the factors which affect the rate of evaporation	P3.01			
describe how a gas causes pressure on its container, and the factors which increase the pressure	P3.02			
describe thermal expansion	P3.03			
describe some applications and consequences of thermal expansion	P3.03			
name the three methods of thermal energy transfer	P3.04			
name some thermal conductors and insulators	P3.04			
explain the role of molecules and electrons in thermal conduction	P3.04			
name the main method of thermal energy transfer in fluids	P3.04			
describe how density changes in fluids cause convection currents	P3.04			
state the method of thermal energy transfer which does not need a medium to travel through	P3.04			
describe experiments to identify the surfaces which best emit and absorb infrared radiation	P3.04			
identify and explain examples of the three methods of thermal energy transfer.	P3.04			

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P4

Properties of waves

All learners study some content in this chapter

IN THIS CHAPTER YOU WILL:

- describe a wave in terms of speed, amplitude, frequency and wavelength
- identify differences between transverse waves and longitudinal waves
- calculate wave speed
- describe reflection and refraction of waves
- describe diffraction of waves
- use the law of reflection of light to explain how an image is formed in a plane mirror
- construct ray diagrams for reflection
- investigate the refraction of light
- draw ray diagrams to show how lenses form images
- describe the difference between real and virtual images
- describe the main features of the electromagnetic spectrum
- describe some uses of different electromagnetic waves

CONTINUED

- consider how electromagnetic waves can be used safely
- describe how sounds are produced and how they travel
- measure the speed of sound
- describe how the amplitude and frequency of a sound wave are linked to its loudness and pitch
- state the range of human hearing.

BEFORE YOU START

In a group, discuss all the different types of wave you can think of.
What do these waves have in common? What do waves do?

SCIENCE IN CONTEXT P4.01

The world in a drop of rain

Figure P4.01: The light is bent by the raindrop, forming an upside down image of the scene.

This raindrop on a blade of glass shows an image of its surroundings (see Figure P4.01). The light rays causing this have travelled about 150 million kilometres from the Sun to the Earth. Some rays striking the grass are absorbed and supply energy for photosynthesis. Others are reflected, allowing you to see the grass. Those rays passing through the water drop are refracted (bent) to form the image that you see.

Notice that the Sun is at the bottom and the trees appear to grow downwards. The image is upside down. Your eyes contain lenses which produce images in a very similar way to the water drop. Light from the Sun reflects from different objects and enters your eyes. The lens forms an upside down image, like the water drop. Your brain knows the image is upside down so automatically turns it upright. It has had years of practice, so you are not aware of this process.

Figure P4.01 has been captured using a camera which also contains a lens to produce an image.

Light travels at 300 million metres per second, so it takes 8 minutes and 20 seconds to travel from the Sun to the Earth. This means that if the Sun stopped producing light, we would not know for 8 minutes and 20 seconds.

In this chapter you will learn more about the processes of reflection and refraction, which can help us explain how light behaves.

When Apollo astronauts visited the Moon, they left behind reflectors on its surface. These are used to measure the distance from the Earth to the Moon. A laser beam is directed from an observatory on Earth so that it reflects back from these reflectors left on the lunar surface. The time taken by the light to travel there and back is measured and, because the speed of light is known, the distance can be calculated.

A similar method can be used with sound waves to measure the depth of water. Sound is reflected from the sea bed and the time taken is measured. Knowing the speed of sound in water allows the depth to be calculated.

Discussion questions

1 How are these two methods similar?
2 What are the differences?
3 Why is light suitable for one and sound for the other?

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P4.01 General wave properties

Describing waves

Waves are one of the ways that energy can be transferred between different energy stores. A **wave motion** is a series of back and forward movements – a **vibration** or **oscillation**. Dropping a stone in a pond causes a series of little waves or **ripples** to spread through the pond (Figure P4.02). Moving one end of a string causes waves to travel along the string (Figure P4.03). In these examples, the water and the string remain in place after the wave passes. All that is transferred is the energy.

Figure P4.02: Ripples in water.

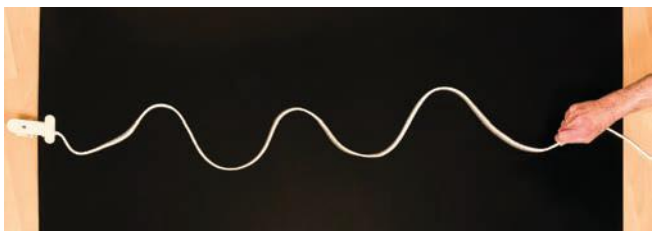

Figure P4.03: A wave in a string.

KEY WORDS

wave motion: the transfer of energy without any transfer of matter.

vibration (oscillation): a repeated back and forth movement.

ripple: a small uniform wave on the surface of water.

Wavelength and amplitude

Waves are often represented by a wavy line, as shown in Figure P4.04. You can think of this as a side view of a water wave. It shows the wave is made up of a succession of **crests** (also called **peaks**) and **troughs**.

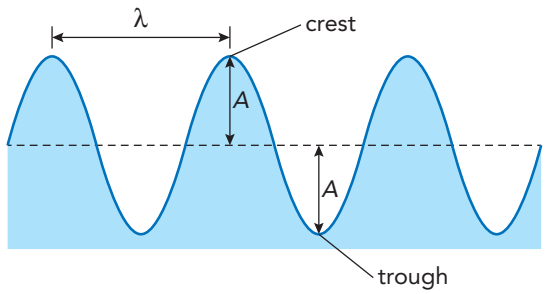

Figure P4.04: A sideways view of a wave.

Two measurements are marked on the graph. These define quantities used to describe waves.

- The **wavelength** of a wave is the distance from one crest of the wave to the next (or one trough to the next). Wavelength is a distance. It is measured in metres, m. Its symbol is λ, the Greek letter lambda.
- The **amplitude**, ***A***, of a wave is the height of a crest (or the depth of a trough). Amplitude is a distance, measured in metres, m. Its symbol is *A*.

Frequency

The **frequency**, ***f***, of a wave is the number of oscillations each second. Figure P4.05 shows a ripple tank which can be used to study water waves. When the motor is switched on it makes the bar vibrate up and down. Each vibration causes a wave in the water.

KEY WORDS

crest/peak: the highest point of a wave.

trough: the lowest point of a wave.

wavelength: the distance between two adjacent crests (or troughs) of a wave.

amplitude (*A*): the greatest height or depth of a wave from its undisturbed position.

frequency (*f*): the number of complete vibrations or waves per second.

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If the bar dips into the water four times each second, we say the waves have a frequency of four waves per second, or 4 **hertz (Hz)**.

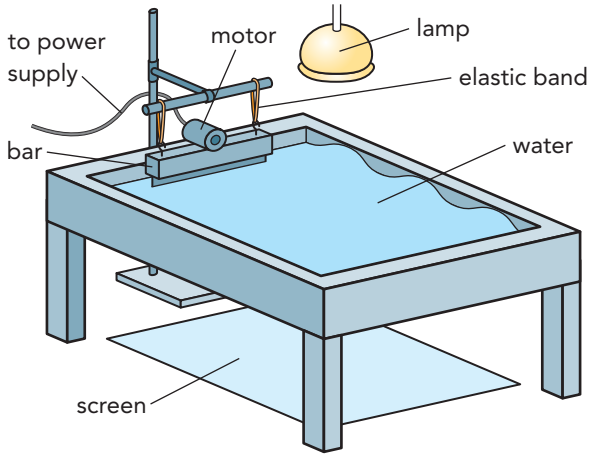

Figure P4.05: A ripple tank can be used to investigate the behaviour of water waves.

Wave speed

The **wave speed** is the rate at which the crest of a wave travels. For example, it could be the speed of the crest of a ripple travelling over the surface of the water. Speed is measured in metres per second (m/s).

Waves can have very different speeds. Ripples in a ripple tank travel a few centimetres per second. Sound waves travel at 330 m/s through air. Light waves travel at about 300 000 000 m/s through air.

KEY WORDS

hertz (Hz): the unit of frequency; 1 Hz = 1 wave per second.

wave speed: the speed at which a wave travels.

Waves and energy

Think of the Sun. It is a source of energy. Its energy reaches us in the form of radiation – light waves and infrared waves – which travels through the vacuum of space and which is absorbed by the Earth.

Think of a loudspeaker. It vibrates and causes the air nearby to vibrate. These vibrations spread out in the air as a sound wave. When the waves reach our ears, our eardrums vibrate. Energy has been transferred by the sound waves to our ears.

The bigger the amplitude, the more energy the wave transfers. A large amplitude means a bright light or a loud sound.

Transverse and longitudinal waves

There are two different types of waves, which can be illustrated using a long 'slinky' spring.

- **Transverse waves**: the particles carrying the wave move from side to side, at right angles to the direction of propagation of the wave (Figure P4.06a).
- **Longitudinal waves**: the particles carrying the wave move back and forth, along the direction of propagation of the wave (Figure P4.06b.) A longitudinal wave is made up of a series of **compressions** (compressed regions) and **rarefactions** (stretched out regions) which move along the wave.

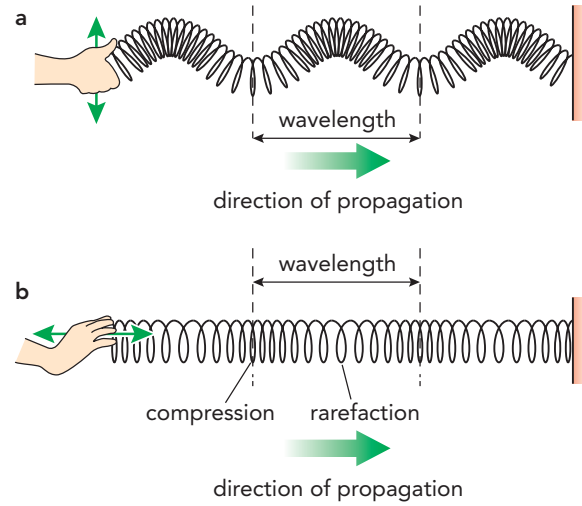

Figure P4.06: Modelling waves using a spring. **a:** A transverse wave on a stretched spring. It is made by moving the free end from side to side. **b:** A longitudinal wave on a stretched spring. It is made by pushing the free end back and forth, along the length of the spring.

KEY WORDS

transverse wave: a wave in which the vibration is at right angles to the direction of propagation of the wave.

longitudinal wave: a wave in which the vibration is forward and back, parallel to the direction of propagation of the wave.

compression: a region of a longitudinal wave where the particles are pushed together.

rarefaction: a region of a longitudinal wave where the particles are further apart.

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A ripple on the surface of water is an example of a transverse wave. The particles of the water move up and down as the wave travels horizontally.

A sound wave is an example of a longitudinal wave. As a sound travels through air, the air molecules move back and forth as the wave travels. Table P4.01 lists examples of transverse and longitudinal waves.

Seismic waves are generated by earthquakes. There are two types of seismic waves. The primary (P) waves are longitudinal and the secondary (S) waves are transverse.

Transverse waves	Longitudinal waves
ripples on water	sound
light and all other electromagnetic waves	seismic P waves
seismic S waves	

Table P4.01: Transverse and longitudinal waves.

Questions

P4.01 Copy and complete the following sentences.

a A wave transfers _____ from place to place without transferring _____.

b In a _____ wave the vibrations are at right angles to the direction in which the wave travels. In a _____ wave the vibrations are back and forth along the direction of the wave.

P4.02 The two waves in Figure P4.07 represent two light waves, X and Y.

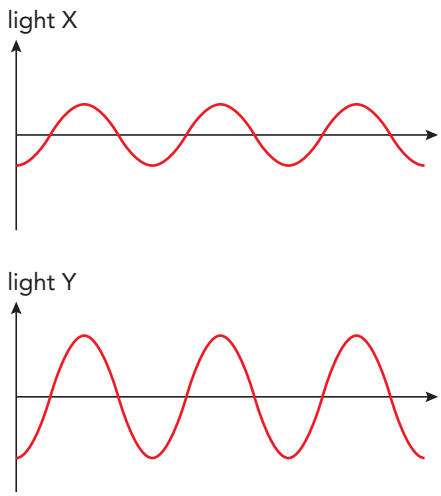

Figure P4.07: Two light waves.

Copy these sentences and select the correct answers.

a The two waves have **the same / different** wavelengths.

b The two waves have **the same / different** amplitudes.

c Light X will be **brighter / dimmer** than light Y.

P4.03 Draw a wave and label the amplitude and the wavelength.

The wave equation

The speed of a wave is determined by the material it is passing through. Figure P4.08 shows waves travelling along a string. Both waves travel at the same speed. The blue wave has a low frequency, whereas the red wave has a high frequency – the end of the string is being moved up and down much faster.

You can see in Figure P4.08 that the blue wave has a much longer wavelength than the red wave.

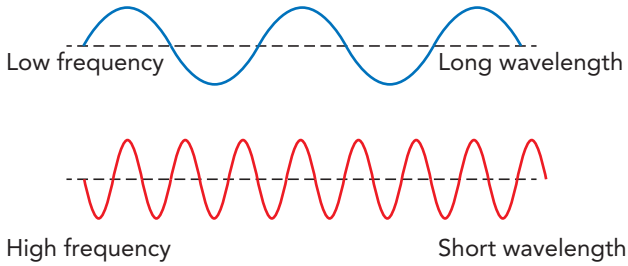

Figure P4.08: Short wavelength = high frequency, long wavelength = low frequency.

The speed, frequency and wavelength of a wave are connected by an equation known as the wave equation:

KEY EQUATION

$$\text{wave speed} = \text{frequency} \times \text{wavelength}$$

$$v = f\lambda$$

Another way to think of this is to say that the speed is the number of waves passing per second multiplied by the length of each wave. If 100 waves pass each second ($f = 100\,\text{Hz}$), and each is 4.0 m long ($\lambda = 4.0\,\text{m}$), then 400 m of waves pass each second. The speed of the waves is 400 m/s.

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WORKED EXAMPLE P4.01

An FM radio station broadcasts signals of wavelength 1.5 metres and frequency 200 MHz. What is their speed?

Step 1: Write down what you know, and what you want to know.

$f = 200\,\text{MHz} = 200\,000\,000\,\text{Hz}$

$= 2 \times 10^8\,\text{Hz}$

$\lambda = 1.5\,\text{m}$

$v = ?$

Step 2: Write down the equation for wave speed. Substitute values and calculate the answer.

$v = f\lambda$

$v = 2 \times 10^8\,\text{Hz} \times 1.5\,\text{m}$

$= 3 \times 10^8\,\text{m/s}$

Answer

The radio waves travel through the air at 3.0×10^8 m/s. (You might recognise this number as the speed of light.)

Questions

P4.04 A sound wave has a frequency of 170 Hz and a wavelength of 2 m. Calculate the speed of the sound wave.

P4.05 A girl measures the length of 10 water waves. The length is 5 m. She measures the speed of the wave as 5 m/s.

a What is the wavelength of the water waves?

b What is the frequency of the water waves?

Explaining wave behaviour

Waves in a ripple tank can be used to show some of the ways that all waves behave.

Reflection

When a wave hits a barrier it is reflected. This **reflection** changes the direction of the wave. The direction of the reflected wave depends on the angle the wave hits the barrier at. Figure P4.09 shows water waves being reflected by a barrier. This is similar to the way light is reflected by a mirror.

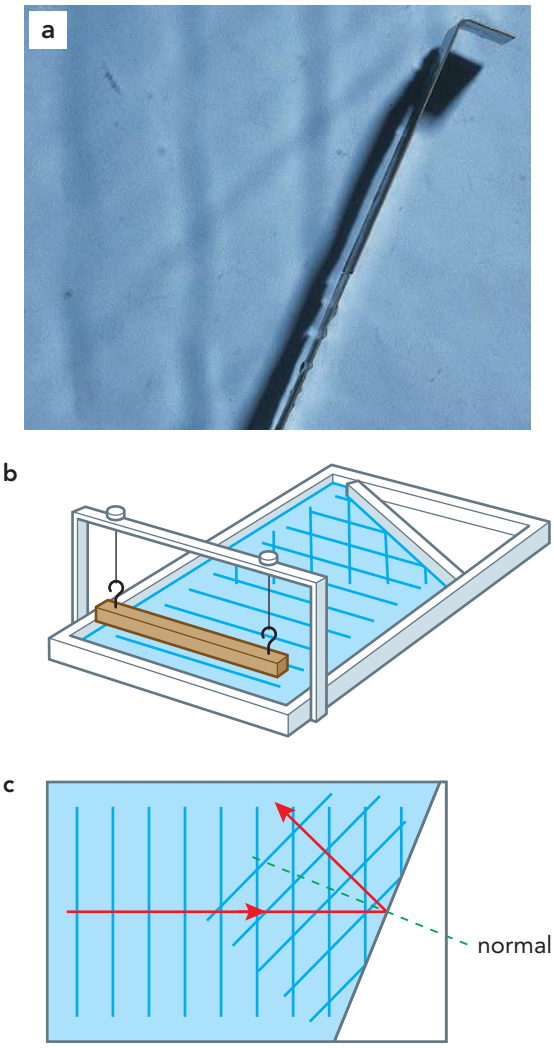

Figure P4.09: The reflection of plane waves by a flat metal barrier in a ripple tank. **a:** This criss-cross pattern is observed as the reflected ripples pass through the incoming ripples. **b:** How the ripples are produced. **c:** The arrows show how the direction of the ripples changes when they are reflected.

Refraction

When waves move from one medium to another, such as from deep water to shallow water, they change speed. This can cause the waves to change direction. This change of direction is called **refraction**.

KEY WORDS

reflection: the change in direction of a ray or wave when it strikes a surface without passing through it.

refraction: the change in direction of a ray or wave when it passes from one medium to another.

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Figure P4.10 shows water waves being refracted as they pass from deep to shallow water. The waves slow down as they go into the shallow water. The parts of the wave which enter the shallow water first are slowed down first and this causes the wave to change direction.

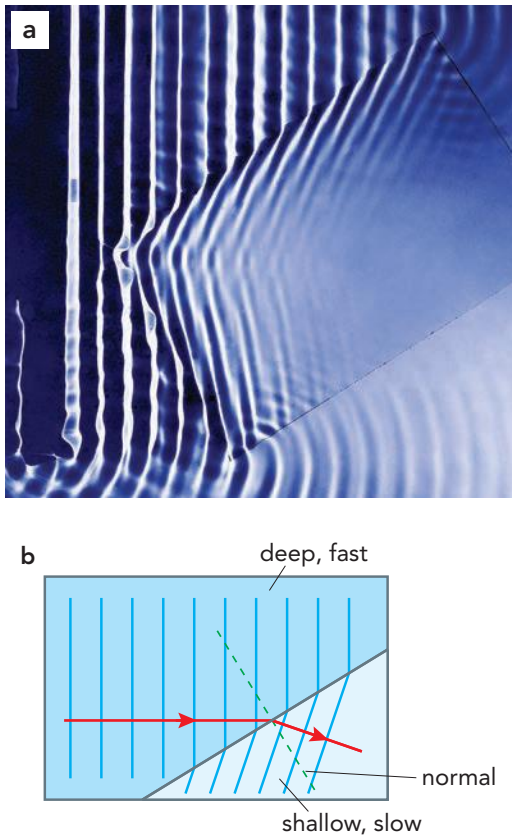

Figure P4.10 a: The refraction of plane waves by a flat glass plate in a ripple tank. A submerged glass plate makes the water shallower. In the shallow region, the ripples move more slowly, so that they lag behind the ripples in the deeper water. **b:** This diagram shows the same pattern of ripples as **a**, with the red arrows showing the change in direction.

Diffraction

An interesting thing happens to waves when they go through a gap in a barrier. Figure P4.11 shows what happens. Waves passing through the gap in the rocks spread out to fill the bay. This is called **diffraction**.

KEY WORD

diffraction: the spreading out of a wave as it travels through a gap.

Figure P4.11: The waves on the sea are straight. As they pass through the gap in the rocks, they start to spread out.

Figure P4.12 shows water waves in a ripple tank being diffracted as they pass through a gap. The waves are diffracted most in Figure P4.12a where the gap is about the same size as the wavelength of the water waves. The waves in Figure P4.12b are only bent at the edges, as the gap is much bigger than the wavelength.

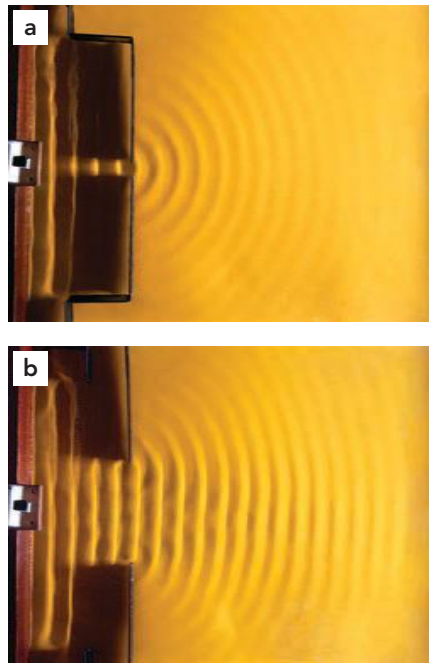

Figure P4.12: Ripples are diffracted as they pass through a gap in a barrier; they spread into the space behind the barrier. **a:** The gap is similar to the wavelength and the waves are diffracted a lot. **b:** The gap is much bigger than the wavelength and the waves are only refracted a bit.

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EXPERIMENTAL SKILLS P4.01

Studying waves in a ripple tank

In this experiment you will observe the behaviour of water waves in a ripple tank.

You will need:

- ripple tank and dipper with an eccentric motor
- power supply
- light
- metal or plastic barriers
- glass sheet to adjust the depth of water.

Safety

It is easiest to observe the shadow of the waves in a darkened room. Keep the work area tidy to avoid trip hazards. Clear up any spilt water immediately.

Getting started

What effect does changing the speed of the motor have on the waves produced?

If you put a small piece of cork in the water, how does it move?

Method

1 Adjust the motor so that you can clearly see the shadows of the waves moving across the tank.
2 Place a barrier in the tank at an angle so that it reflects the waves.
3 Look carefully at the reflected waves. Investigate what happens when you change the angle of the barrier.
4 Place the glass sheet in the tank so that the waves hit it straight on. Adjust the water level so that the water above the glass is very shallow.
5 Observe the waves as they enter and leave the shallower water.
6 Investigate the effect of turning the glass sheet so that the waves enter the shallow water at an angle.
7 Use two barriers to create a wide gap for the waves to pass through. Observe the effect.
8 Narrow the gap until it is about the same size as the wavelength of the waves. Observe how this affects the waves.

Questions

1 Draw a diagram to show what happens to plane waves when they strike a flat reflector placed at 45° to their direction of travel.

CONTINUED: P4.01

2 Draw a diagram to show what happens to plane waves when:
   a they enter the shallower water straight on
   b they enter shallower water at an angle.
3 Draw diagrams to show diffraction at a wide gap and at a narrow gap.
4 How can the speed of ripples in a ripple tank be changed?

Self assessment

Compare your ripple tank diagrams to another student's. Think about what makes a good diagram. Are your diagrams clear, simple and correctly labelled? Add notes to your diagrams saying what you have done well and what could be improved.

ACTIVITY P4.01

Learning the definitions of key words

You will have noticed that this topic contains a lot of key words. To explain waves you need to be familiar with these words, which describe wave characteristics and how waves behave.

Design and make a revision activity to help you remember the key definitions. You could use one of the ideas below or create your own.

- Flash cards: have a key word on one side and its definition on the other. This way, anything you get wrong, you will see the correct answer straight away which will help for the next time.
- Questions: write a set of short questions such as, 'What is the unit of frequency?' on a large sheet of paper. Give each question a mark (1 for easy, 2 for difficult). With a friend, take turns answering questions. Remove any which have been answered correctly as you go. The winner is the person with most points.
- Create self-test questions on a quiz app. This way you can test yourself regularly and quickly.

Reflection

Learning key words is important in physics as words have very precise meanings which may be different from the everyday use of the word. Think about how you learn these words. What activities are most helpful for you? Are you regularly checking back over key words from other chapters? Have you learnt revision techniques in other subjects which you can apply here?

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Questions

P4.06 Figure P4.13 shows four sets of ripples, a–d, in a ripple tank. Copy and complete each diagram to show what happens to the ripples. Label each diagram with the wave phenomenon it is showing.

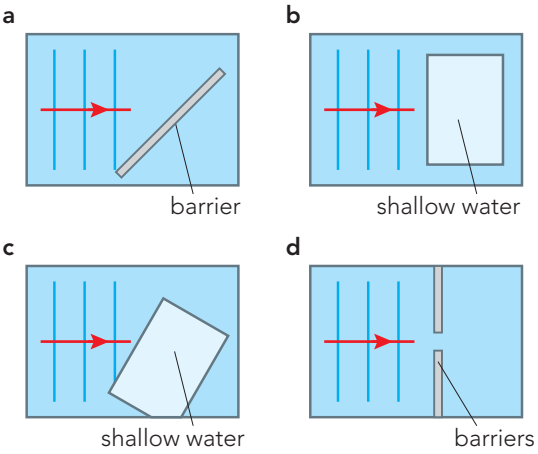

Figure P4.13: These diagrams show a bird's eye view of waves in a ripple tank. They each show different wave behaviours: **a:** reflection, **b:** change of wave speed in a different medium, **c:** refraction, **d:** diffraction.

P4.07 The red lines in Figure P4.14 show sound waves created by person A.

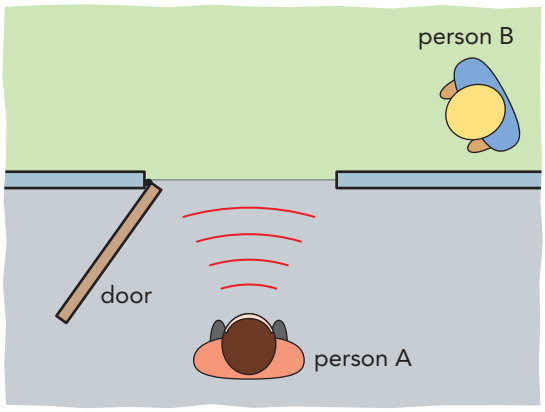

Figure P4.14: Refraction of sound waves.

a Copy and complete Figure P4.14 to show how the sound waves reach person B.

b What type of waves are sound waves?

P4.02 Light

Reflection of light

Light usually travels in straight lines. It changes direction if it hits a shiny surface. This change in direction at a shiny surface such as a mirror is called reflection. We will look at reflection in this topic.

You can use a **ray box** to show that light travels in a straight line. This is shown in Figure P4.15. A light bulb produces light, which spreads out in all directions. A ray box produces a broad beam. By placing a narrow slit in the path of the beam, you can see a single narrow beam or **ray** of light. The ray shines across a piece of paper. You can record its position by making dots along its length. Laying a ruler along the dots shows that they lie in a straight line.

KEY WORDS

ray box: apparatus used to produce a ray of light.

ray: a narrow beam of light.

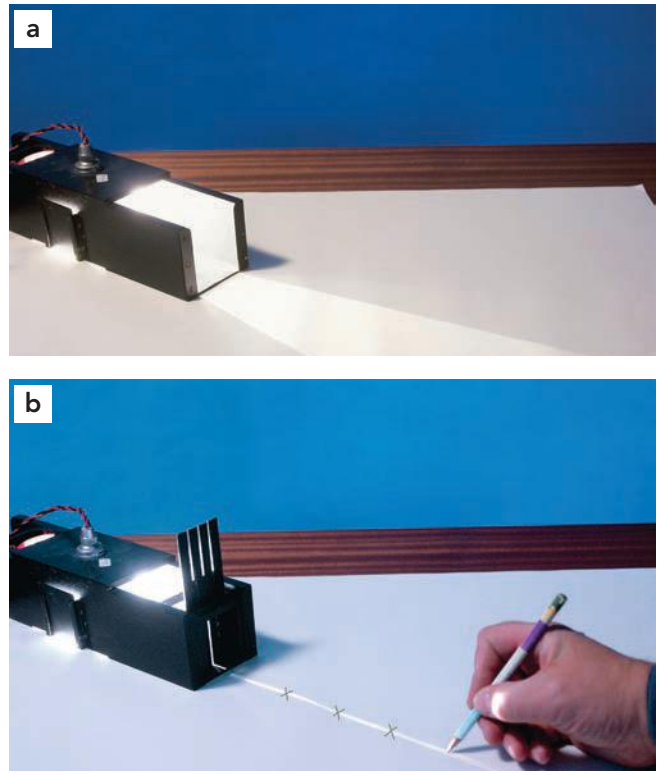

Figure P4.15 a: A ray box produces a broad beam of light, which can be narrowed down using a metal plate with a slit in it. **b:** Marking the line of the ray with crosses allows you to record its position.

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When a ray of light reflects off a mirror or other reflecting surface, it bounces off, rather like a ball bouncing off a wall. The ray which hits the mirror is called the **incident ray** and the ray which bounces off the mirror is called the **reflected ray**.

The **normal** is a line drawn at right angles to the mirror at the point where the ray strikes the mirror. The angles of incidence and reflection are measured between the rays and the normal. Figure P4.16 shows this on a **ray diagram**.

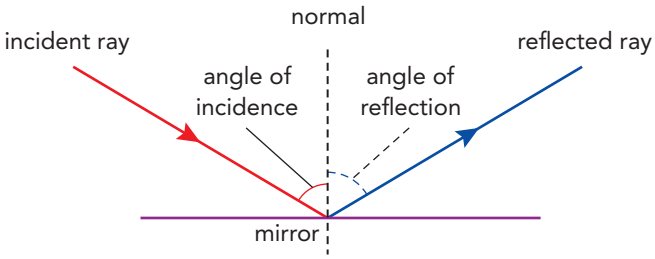

Figure P4.16: This ray diagram shows the reflection of light. The normal is drawn at 90° to the mirror. Then the angles are measured between the rays and the normal. The angle of incidence and the angle of reflection are equal: $i = r$.

Experiments show that the **angle of incidence**, ***i***, and the **angle of reflection**, ***r***, are equal to each other. This is the law of reflection:

KEY EQUATION

angle of incidence = angle of reflection

$$i = r$$

KEY WORDS

incident ray: a ray of light arriving at a surface.

reflected ray: a ray of light which has been reflected from a surface.

normal: the line drawn at right angles to a surface at the point where a ray hits the surface.

ray diagram: a diagram showing the path of rays of light.

angle of incidence (*i*): the angle between the incident ray and the normal drawn at the point where the ray hits the surface.

angle of reflection (*r*): the angle between the reflected ray and the normal drawn at the point where the ray hits the surface.

ACTIVITY P4.02

Investigating the law of reflection

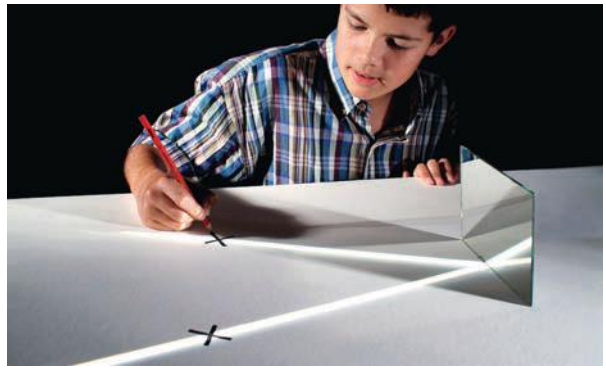

Figure P4.17: Investigating the law of reflection.

The student in Figure P4.17 is investigating the law of reflection.

Write step-by-step instructions for his investigation. Include a list of the apparatus needed, and the measurements that he should take.

The image in a plane mirror

Why do we see such a clear **image** when we look in a **plane mirror**? And why does it appear to be behind the mirror?

Figure P4.18a shows how an observer sees an image of a candle in a plane mirror. Light rays from the candle are reflected by the mirror. Some of them enter the observer's eye.

Figure P4.18b shows how the image is formed. The solid lines show the light from the candle reflecting from the mirror. The girl's brain assumes that the rays have travelled in straight lines from a point behind the mirror, shown by the dashed lines. (Our brains assume that light travels in straight lines, even though we know that light is reflected by mirrors.) In reality, no light is coming from behind the mirror. The dashed lines appear to be coming from a point behind the mirror, at the same distance behind the mirror as the candle is in front of it. You can see this from the symmetry of the diagram.

KEY WORDS

image: what we see when we view an object by means of reflected rays.

plane mirror: (or a flat mirror) a mirror with a flat, reflective surface.

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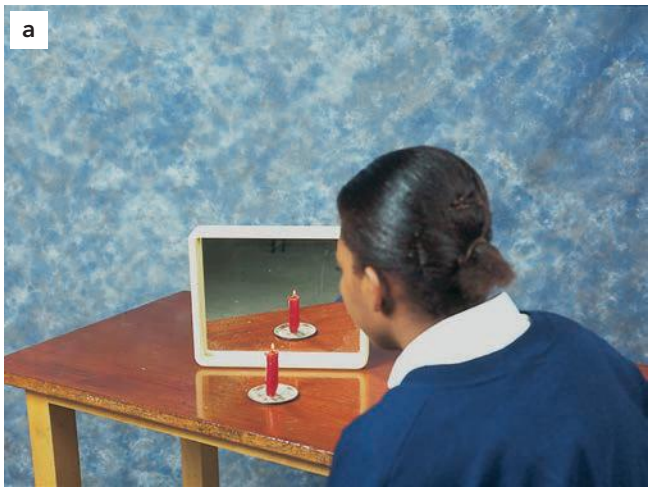

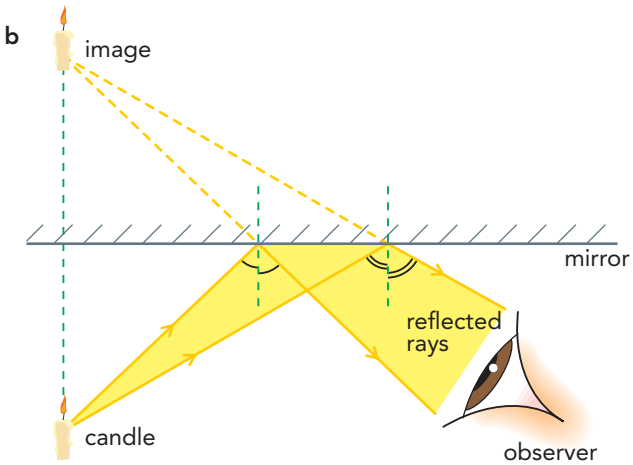

Figure P4.18 a: Looking in the mirror, the observer sees an image of the candle. The image appears to be behind the mirror. **b:** The ray diagram shows how the image is formed. Rays from the candle flame are reflected according to the law of reflection.

The image looks as though it is the same size as the candle. Also, it is (of course) a mirror image – it is left–right reversed, or **laterally inverted**. You will know this if you have seen writing reflected in a mirror. If you could place the object and its image side-by-side, you would see that they are mirror images of each other, in the same way that your left and right hands are mirror images of each other.

The image of the candle in the mirror is not a real image. A **real image** is an image that can be formed on a screen. If you place a piece of paper at the position of the image, you will not see a picture of the candle on it, because no rays of light from the candle reach that spot. That is why we drew dashed lines, to show where the rays appear to be coming from. We say that it is a **virtual image**.

KEY WORDS

laterally inverted: an image in which left and right have been reversed.

real image: an image that can be formed on a screen.

virtual image: an image that cannot be formed on a screen.

To summarise, when an object is reflected in a plane mirror, its image is:

- the same size as the object
- the same distance behind the mirror as the object is in front of it
- laterally inverted
- virtual.

Questions

P4.08 **a** Look at Figure P4.19. Why is the word 'AMBULANCE' written in reverse on the front of the vehicle?

Figure P4.19: The word 'AMBULANCE' is in mirror writing.

b Write the word POLICE in the same way.

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P4.09 A student investigated the law of reflection. She increased her angle of incidence by 20° each time, as shown in Table P4.02.

Angle of incidence	Angle of reflection
20°	20°
40°	39°
60°	30°

Table P4.02: A comparison of angles of incidence and refraction.

a Which angle of reflection did she measure incorrectly?

b Suggest what she may have done wrong.

P4.10 Draw a diagram to show a ray hitting a mirror with an angle of incidence of 40°. Draw the reflected ray. Label both rays, the normal, and the angles of incidence and reflection.

P4.11 Figure P4.20 shows how a periscope uses mirrors to allow the user to see beyond obstacles.

a Copy and complete Figure P4.20 to show how the light reaches the observer.

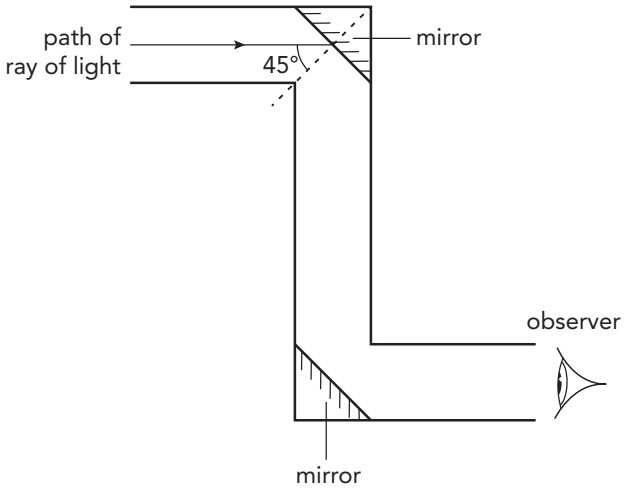

Figure P4.20: A periscope uses the reflection of light rays.

b The image the observer sees is not laterally inverted. Explain why.

Ray diagrams

Light rays follow strict rules. By following the same rules we can construct detailed ray diagrams. These show where an image is formed and what type of image it is. Worked example P4.02 shows the steps in constructing a ray diagram to show the formation of an image in a plane mirror.

WORKED EXAMPLE P4.02

A small lamp is placed 5 cm in front of a plane mirror. Draw an accurate scale diagram, and use it to show that the image of the lamp is 5 cm behind the mirror.

The steps needed to draw the ray diagram are listed below and shown in Figures P4.21a–d. (It helps to work on squared paper or graph paper.)

Step 1: Draw a line to represent the mirror. Indicate its reflecting surface by drawing short lines on the back of the line. Mark the position of the object (the lamp) with a cross and label it.

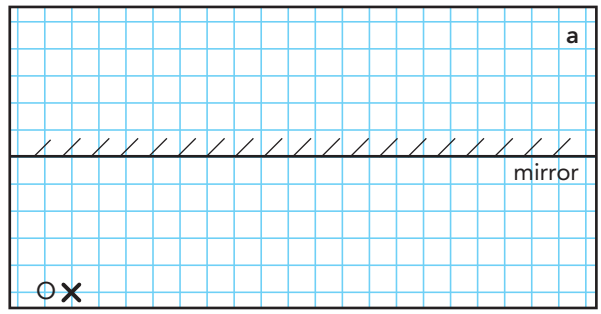

Figure P4.21 a: O shows the position of the object.

Step 2: Draw two rays from the object to the mirror. Draw in the normal lines where they strike the mirror.

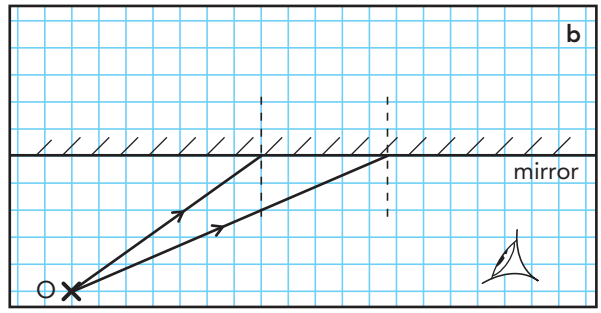

Figure P4.21 b: Rays from the object hit the mirror.

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CONTINUED

Step 3: Using a protractor, measure the angle of incidence for each ray. Mark the equal angle of reflection. Draw in the reflected rays.

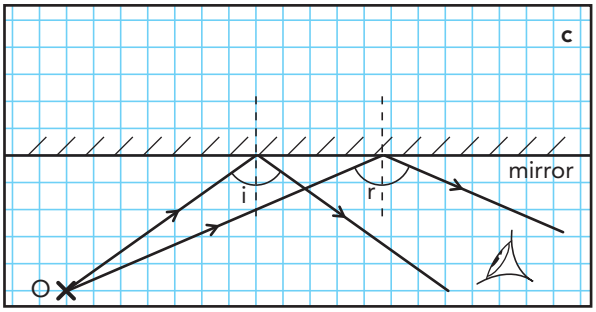

Figure P4.21 c: The rays are reflected following the law of reflection.

Step 4: Extend the reflected rays back behind the mirror. Draw this using dotted lines. The point where they cross is where the image is formed. Label this point I.

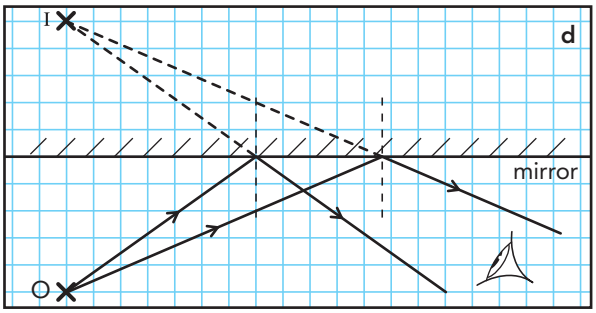

Figure P4.21 d: The observer assumes the rays have travelled in a straight line and so sees an image at the point marked I.

Answer

From the diagram for step 4, it is clear that the image is 5 cm from the mirror, directly opposite the object. The line joining O to I is perpendicular to the mirror.

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Question

P4.12 Figure P4.22 shows an object placed 6 cm from a plane mirror.

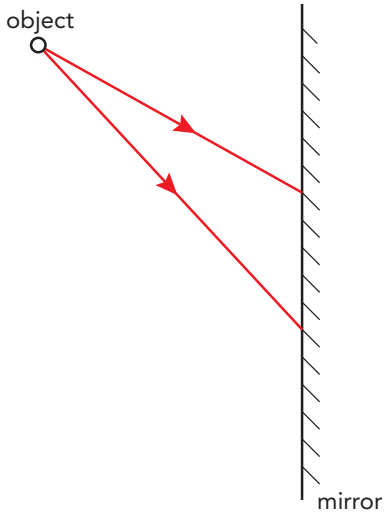

Figure P4.22: An incomplete ray diagram for a plane mirror.

a Copy the diagram and use the law of reflection to find the path of the rays after they hit the mirror.

b Trace these rays back to find the position of the image.

c Measure the perpendicular distance from the image to the mirror.

Refraction of light

If you look down at the bottom of a swimming pool, you may see patterns of shadowy ripples as in Figure P4.23.

Figure P4.23: The ripples seen on the bottom of the pool are caused by water bending the light.

The surface of the water is not flat. There are often small ripples on the water, and these cause the rays of sunlight to change direction, creating areas of light and shade. This bending of light is called refraction.

The apparently bent straw in liquid (Figure P4.24) is another consequence of refraction.

Figure P4.24: The straw is partly immersed in the drink. Because of the refraction of the light coming from the part of the straw that is underwater, the straw appears bent.

Refraction occurs when a ray of light travels from one medium into another. The ray of light may change direction. Refraction happens at the boundary between the two materials.

Figure P4.25 shows light passing through a rectangular block. Notice that the light only bends at the point where it enters or leaves the block, so it is the change of material that causes the bending.

From Figure P4.25, you can see that the direction in which the ray bends depends on whether it is entering or leaving the glass.

- The ray bends towards the normal when entering the glass.
- The ray bends away from the normal when leaving the glass.

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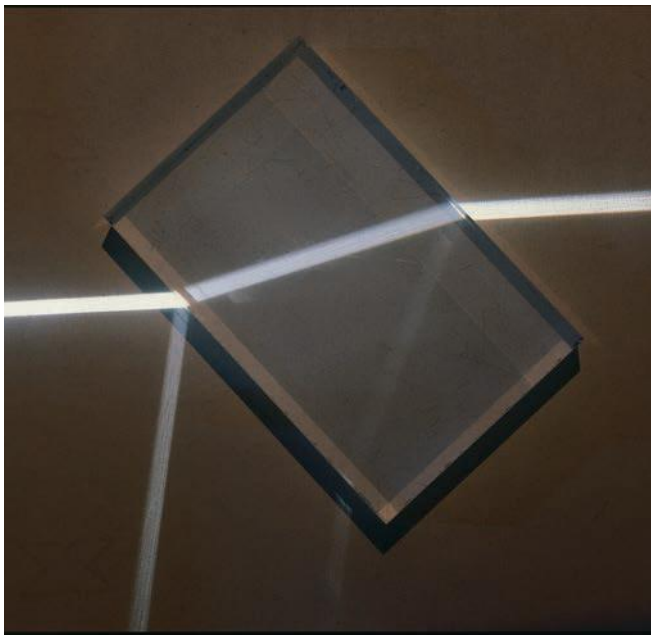

Figure P4.25: Demonstrating the refraction of a ray of light when it passes through a rectangular block of glass or Perspex. The ray bends as it enters the block. As it leaves, it bends back to its original direction.

Changing direction

The ray approaching the boundary is called the incident ray and the ray leaving the boundary is called the refracted ray. The angle of incidence, i, and **angle of refraction**, r, are measured to the normal drawn at the point where the ray hits the boundary (see Figure P4.26).

KEY WORDS

angle of refraction (r): the angle between a refracted ray and the normal to the surface at the point where it passes from one medium to another.

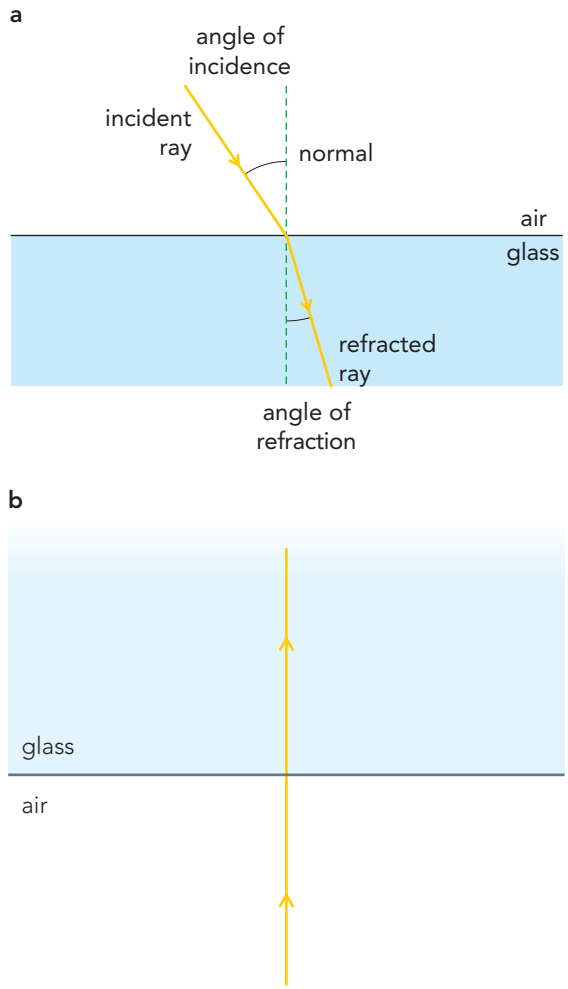

Figure P4.26: Refraction of a light ray entering glass. **a:** Notice that the angles of incidence and refraction are measured relative to the normal. **b:** When a ray strikes the glass at 90° it carries straight on.

EXPERIMENTAL SKILLS P4.02

Investigating refraction

You can investigate refraction by shining a ray of light into a glass or *Perspex* block and tracing the path of the ray.

Safety

You will be working in a darkened area, so keep your work area tidy to avoid trip hazards.

You will need:

- ray box
- power pack
- rectangular glass or *Perspex* block
- glass or *Perspex* of different shapes
- plain paper.

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CONTINUED: P4.02

Getting started

1 How will you mark the path of the rays going in and out of the block?

2 How will you determine the path of the ray inside the glass block?

Method

1 Place the block on paper and draw round it.

2 Shine a ray into the block as shown in Figure P4.27. Look carefully at the ray inside the glass. You will see it travels in a straight line. It only bends at the surface.

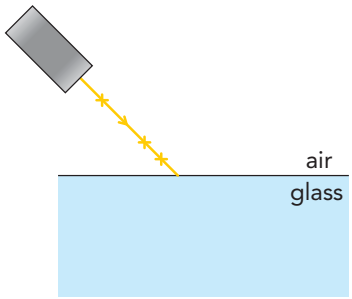

Figure P4.27: Ray hitting the glass block.

3 Mark the ray going into the block and the ray coming out of the block with crosses.

4 Remove the block and draw the ray going into the block and the ray coming out.

5 Join these two rays to show the path of the light through the glass.

6 Draw the normal at the points where the ray enters and leaves the block.

7 Measure angles *i* and *r* for the ray entering the block and record them in a table.

Angle of incidence in air, *i*	Angle of refraction in glass, *r*

8 Repeat this for rays entering the block at different angles.

9 If you have blocks of different materials, repeat the experiment to find out which material bends light the most.

10 Investigate what happens if a ray of light hits the glass block at 90°.

Questions

1 Copy and complete these sentences:

When a ray goes from air to glass it bends _____ the normal.

For a ray going from air to glass, the angle of _____ is smaller than the angle of _____.

When a ray goes from glass to air it bends _____ the normal.

2 Describe what happens when a ray hits the block at 90°.

Questions

P4.13 Describe what happens to a ray of light that passes from:

a air to glass

b glass to air.

P4.14 Draw a diagram to show a light ray passing from glass to air. Mark the incident and refracted rays, the normal and the angles of incidence and refraction.

Refractive index

Light travels very fast. As far as we know, nothing can travel any faster than light. The **speed of light** as it travels though empty space is exactly 299 792 458 m/s. This is usually rounded to 300 000 000 m/s or 3×10^8 m/s.

When a ray of light passes from air into glass, it slows down and bends towards the normal. This happens when light passes from one transparent medium to another, or when light passes between different regions, such as from hot water to cold water. Table P4.03 shows the speed of light in different media.

The **refractive index** of a material is a measure of how much the light slows, or how much it is bent. If the speed of light is halved when it enters a material, the refractive index is 2, and so on. The refractive index is the ratio of the speeds of light in two different media or different regions.

KEY WORDS

speed of light: the speed at which light travels (usually in a vacuum: 3.0×10^8 m/s).

refractive index: the ratio of the speeds of a light wave in two different media.

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KEY EQUATION

$$\text{refractive index, } n = \frac{\text{speed in vacuum}}{\text{speed in material}}$$

Material	Speed of light / m/s	$\frac{\text{speed in vacuum}}{\text{speed in material}}$
vacuum	2.998×10^8	1 exactly
air	2.997×10^8	1.0003
water	2.254×10^8	1.33
Perspex®	2.000×10^8	1.5
glass	$(1.800–2.000) \times 10^8$	1.5–1.7
diamond	1.250×10^8	2.4

Table P4.03: The speed of light in some transparent materials. Note that the values are only approximate.

Calculating refractive index

ACTIVITY P4.03

Interpreting data

You can use the measurements you took in Experimental skills P4.02 to investigate the relationship between the angles of incidence and refraction.

Angle of incidence, i	Angle of refraction, r	$\sin i$	$\sin r$	$\frac{\sin i}{\sin r}$

Use a calculator or tables to find the sine of each angle, and divide $\sin i$ by $\sin r$.

If you investigated different blocks, draw and complete a table for each.

Question

1 What can you conclude about the value of $\frac{\sin i}{\sin r}$?

The value of $\frac{\sin i}{\sin r}$ is always the same for a particular material. This value is the refractive index of the material. The refractive index of glass is about 1.5 and the refractive index of water is about 1.33.

Refractive index (n) can be calculated using the equation:

KEY EQUATION

$$n = \frac{\sin i}{\sin r}$$

WORKED EXAMPLE P4.03

A ray of light hits the surface of water at an angle of incidence of 30°. It is refracted at an angle of 22°. Find the refractive index, n, of water.

Step 1: Write down what you know and what you want to find out.

$i = 30°$

$r = 22°$

$n = ?$

Step 2: Write down the equation and substitute these values.

$$n = \frac{\sin i}{\sin r} = \frac{\sin 30}{\sin 22}$$

Step 3: Use a calculator or tables to find the sines and calculate n.

$$n = \frac{0.5}{0.375}$$
$$= 1.33$$

Answer

$n = 1.33$

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Questions

P4.15 A ray of light enters a block of glass at an angle of incidence of 40°. The angle of refraction in the glass is 25°. Calculate the refractive index of the glass.

P4.16 Figure P4.28 shows a ray of light passing from air into an unknown material (X). The ray is deflected by 19°.

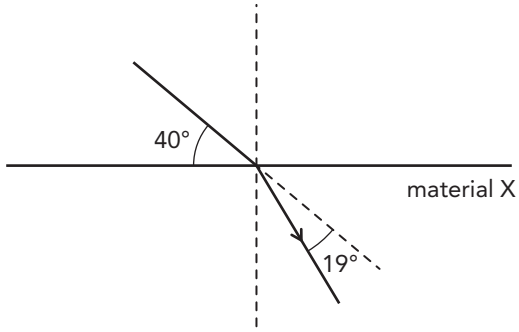

Figure P4.28: Ray of light passing from air into an unknown medium.

a Determine the angles of incidence and refraction.

b Calculate the refractive index of material X. Give your answer to two significant figures.

P4.17 Refraction can happen when light passes from one transparent solid to another. Use the information in Table P4.03 to determine what will happen to a ray of light passing from diamond to glass. Sketch a diagram to show what will happen.

P4.18 A ray of light enters glass with a refractive index of 1.52 at an angle of incidence of 60°. Find:

a the angle of refraction

b the speed of light in the glass.

Total internal reflection

When you investigated refraction you may have noticed that not all the light is refracted. Some is reflected back from the surface, as shown in Figure P4.29. You can also see that as the light emerges from the glass, some light is reflected back inside the glass. This is called **internal reflection**.

Like all reflected light, these reflected rays obey the law of reflection:

angle of incidence = angle of reflection

Rays reflected back inside materials such as glass can be very useful. Figure P4.30 shows internal reflection. A ray of light strikes a semicircular glass block. The ray enters the curved side of the block at right angles and so passes straight through to the midpoint of the straight side.

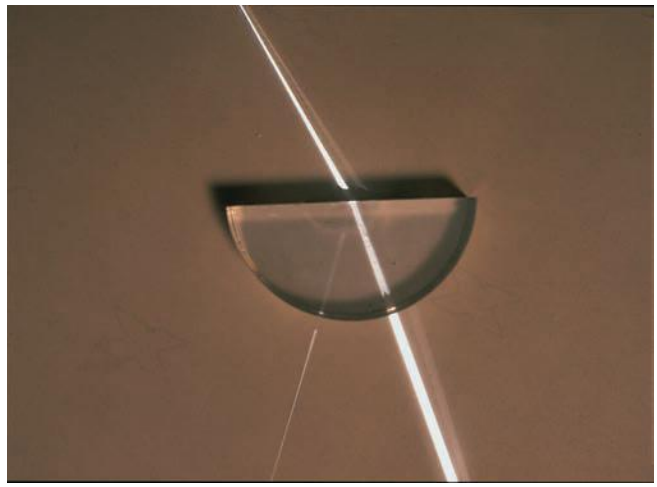

Figure P4.29: Using a ray box to investigate reflection when a ray of light strikes a glass block. The ray enters the block without bending, because it is directed along the radius of the block.

What happens next depends on the angle of incidence of the ray at the midpoint. Figure P4.30 shows the possibilities.

In Figure P4.30a, the angle of incidence is small, so most of the light emerges from the block. There is a faint reflected ray inside the glass block. The refracted ray bends away from the normal.

In Figure P4.30b, the angle of incidence has increased, so more light is reflected inside the block. The refracted ray bends even further away from the normal.

In Figure P4.30c, the angle of refraction is 90°: the ray emerges parallel to the surface. The angle of incidence when this happens is called the **critical angle**.

In Figure P4.30d, the angle of incidence is greater than the critical angle and all of the light is reflected inside the block. No refracted ray emerges from the block.

KEY WORDS

internal reflection: when a ray of light strikes the inner surface of a material and some of it reflects back inside it.

critical angle: the minimum angle of incidence at which total internal reflection occurs.

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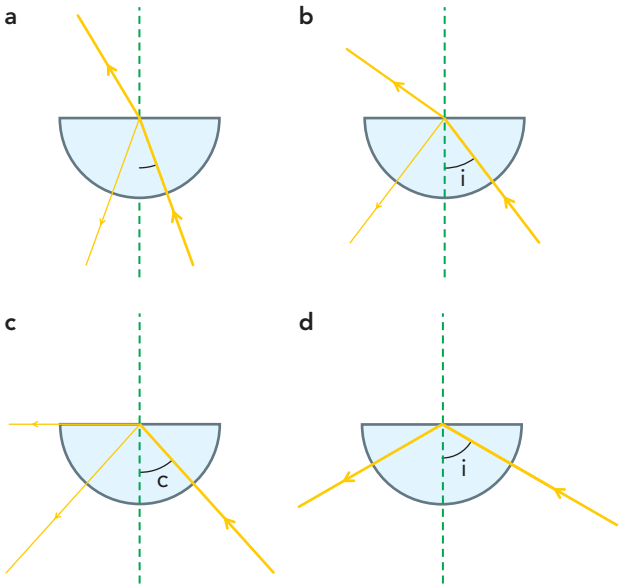

Figure P4.30: How a ray of light is reflected or refracted inside a glass block depends on the angle of incidence.

We have been looking at how light is reflected inside a glass block. We have seen that, if the angle of incidence is greater than the critical angle, the light is entirely reflected inside the glass. This is known as **total internal reflection (TIR)**:

- total, because 100% of the light is reflected
- internal, because it happens inside the glass
- reflection, because the ray is entirely reflected.

For total internal reflection to happen, the angle of incidence of the ray must be greater than the critical angle. The critical angle depends on the material being used. For glass, it is about 42°, depending on the type of glass. For water, the critical angle is greater, about 49°. For diamond, the critical angle is small, about 25°. Rays of light that enter a diamond are very likely to be totally internally reflected, so they bounce around inside, eventually emerging from one of the diamond's cut faces. That explains why diamonds are such sparkly jewels.

KEY WORDS

total internal reflection (TIR): when a ray of light strikes the inner surface of a material and 100% of the light reflects back inside it.

Questions

P4.19 Explain the meaning of the words 'total' and 'internal' in the expression 'total internal reflection'.

P4.20 The critical angle for water is 49°. If a ray of light strikes the upper surface of a pond at an angle of incidence of 45°, will it be totally internally reflected? Explain your answer.

P4.21 Look at Figure P4.31.

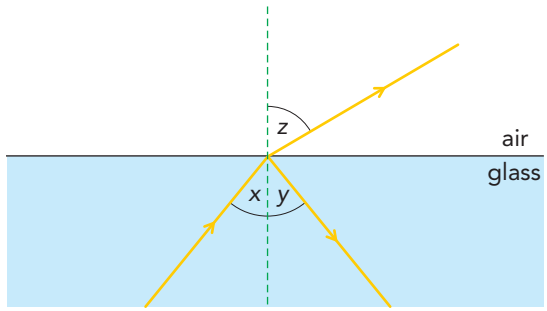

Figure P4.31: Light passing from glass to air can be reflected or refracted.

a Name angles x, y and z.

b Write down any relationships you know between the angles.

c What will happen when angle x is increased?

Optical fibres

A revolution in telecommunications has been made possible by the invention of fibre optics. Telephone messages and other electronic signals, such as internet computer messages or cable television signals, are passed along fine glass fibres in the form of flashing laser light, which is a digital signal. Figure P4.32a shows how fine these fibres can be. Each of these fibres is capable of carrying thousands of telephone calls simultaneously.

Inside a fibre, light travels along by total internal reflection (see Figure P4.32b). It bounces along inside the fibre because, each time it strikes the inside of the fibre, its angle of incidence is greater than the critical angle. This means no light is lost as it is reflected. The fibre can follow a curved path and the light bounces along inside it, following the curve. For signals to travel over long distances, the glass used must be of a very high purity, so that it does not absorb the light.

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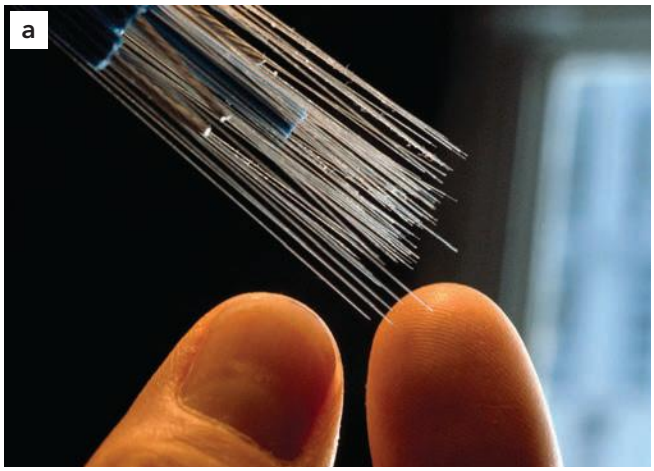

Figure P4.32: The use of fibre optics has greatly increased the capacity and speed of the world's telecommunications networks. Without this technology, cable television and the internet would not be possible. **a:** Each of these very fine fibres of high-purity glass can carry many telephone messages simultaneously. **b:** Light travels along a fibre by total internal reflection.

Optical fibres are also used in medicine. An endoscope is a device that can be used by doctors to see inside a patient's body, for example, to see inside the stomach (Figure P4.33). One bundle of fibres carries light down into the body, while another bundle carries an image back up to the user. The endoscope may also have a small probe or cutting tool built in, so that minor operations can be performed without the need for major surgery.

Light can be used in sensory play to soothe or stimulate children with sensory processing issues. Using optical fibres means children can play freely with lights with no risk of electrocution or burning.

Figure P4.33: Passing a fibre optic cable down the oesophagus to the stomach allows the doctor to see inside the patient without the need for major surgery.

Questions

P4.22 List *two* uses of total internal reflection.

P4.23 Figure P4.34 shows a bicycle reflector. It reflects light by total internal reflection.

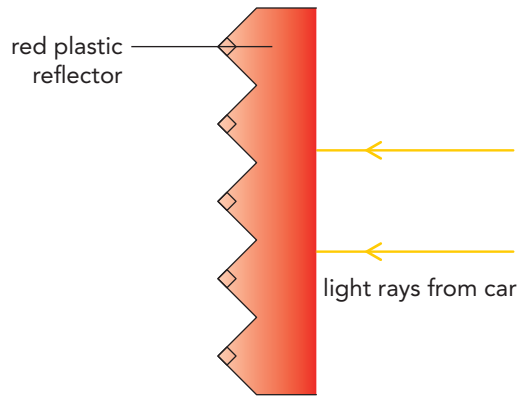

Figure P4.34: How light is reflected in a bicycle reflector.

a Why is light not refracted when it enters the plastic?

b What is the angle of incidence at the diagonal surface?

c Copy and complete the diagram in Figure P4.34 to show the path of the rays from the car.

d What can you deduce about the critical angle of the plastic?

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Thin converging lens

Lenses are all around us, for example in spectacles and cameras. Lenses are particularly important to scientists in instruments including microscopes and telescopes.

We will look at one type of lens, known as a **converging lens**. These lenses are thicker in the middle than at the edges and make rays of light bend towards each other (converge). Figure P4.35 shows some converging lenses.

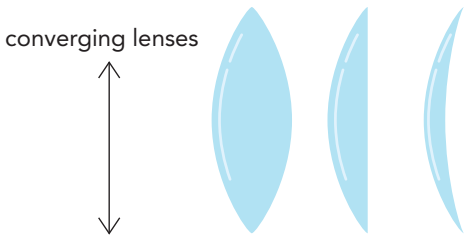

Figure P4.35: Converging lenses are fattest in the middle. Usually, we simply draw the cross-section of the lens.

To show the effect of converging lenses on light, we will use diagrams showing what happens to parallel beams of light. We can assume that rays from a distant object are parallel, as Figure P4.36 explains.

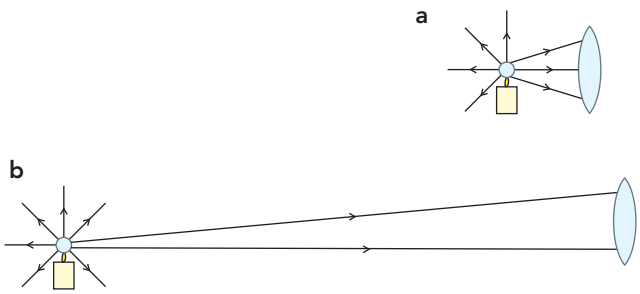

Figure P4.36 a: The rays from an object close to the lens are diverging when they hit the lens. The rays from a more distant object are diverging much less. **b:** We can assume that rays from a distant object are parallel.

Figure P4.37a shows how a converging lens focuses parallel rays. On one side of the lens, the rays are parallel to the **principal axis** of the lens. After they pass through the lens, they converge on a single point: the **principal focus (or focal point)**. After they have passed through the principal focus, they spread out again. A converging lens can be used to produce a beam of parallel rays. A source of light, such as a small light bulb, is placed at the principal focus.

As they pass through the lens, the rays are bent so that they become a parallel beam (Figure P4.37b). This diagram is the same as Figure P4.36a, but in reverse.

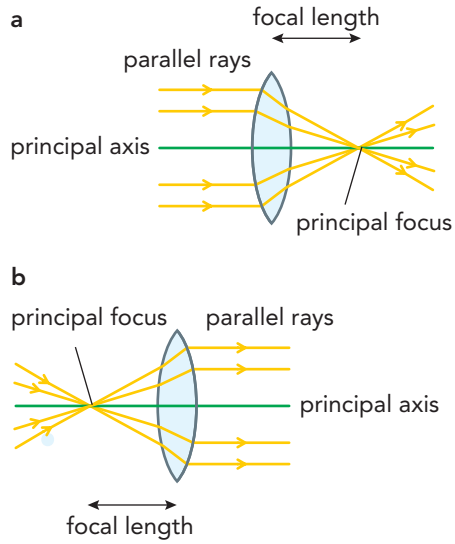

Figure P4.37: The effect of a converging lens on rays of light. **a:** A converging lens makes parallel rays converge at the principal focus. **b:** Rays from the principal focus of a converging lens are turned into a parallel beam of light.

A converging lens is so-called because it makes parallel rays of light converge. The principal focus is the point where the rays are concentrated together, and where a piece of paper needs to be placed if it is to be burnt. The distance from the centre of the lens to the principal focus is called the **focal length** of the lens. The fatter the lens, the closer the principal focus is to the lens. A fat lens has a shorter focal length than a thin lens. Figure P4.38 shows this.

KEY WORDS

converging lens: a lens that causes rays of light parallel to the axis to converge at the principal focus.

principal axis: the line passing through the centre of a lens perpendicular to its surface.

principal focus (or focal point): the point at which rays of light parallel to the principal axis converge after passing through a converging lens.

focal length: the distance from the centre of the lens to its principal focus.

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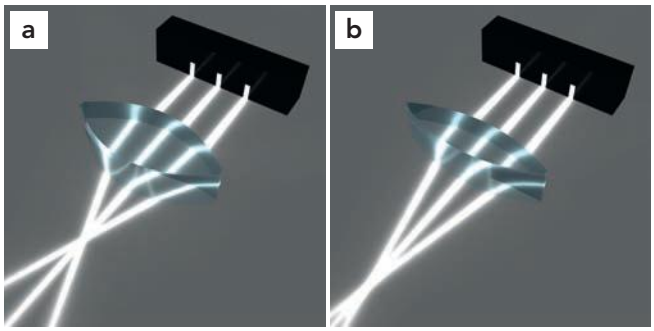

Figure P4.38 a: A fatter lens is more powerful so bends the light more. This gives a shorter focal length. **b:** A thinner lens is not as powerful and does not bend the light as much.

Lenses work by refracting light. When a ray strikes the surface of the lens, it is refracted towards the normal. When it leaves the glass of the lens, it bends away from the normal. The clever thing about the shape of a converging lens is that it bends all rays just enough for them to meet at the principal focus.

Forming an image

When the Sun's rays are focused onto a piece of paper, a tiny image of the Sun is created. It is easier to see how a converging lens makes an image if you focus an image of a light bulb or a distant window onto a piece of white paper. The paper acts as a screen to catch the image. (Be careful if you try this yourself – you could set fire to the paper or burn yourself. And remember: never look directly at the Sun.)

Figure P4.39 shows an experiment in which an image of a light bulb (the object) is formed by a converging lens.

Images can be described in terms of their size (**enlarged**, the same size, or **diminished**), which way up they are (**inverted** or **upright**), and where they are formed.

KEY WORDS

enlarged: used to describe an image which is bigger than the object.

diminished: used to describe an image which is smaller than the object.

inverted: used to describe an image which is upside down compared to the object.

upright: used to describe an image which is the same way up as the object.

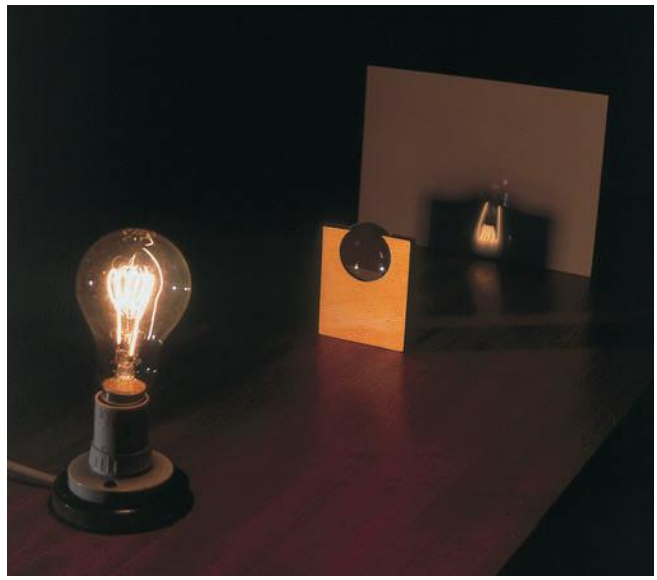

Figure P4.39: Forming a real image of a light bulb using a converging lens. The image is upside down on the screen at the back right.

The image of the light bulb in Figure P4.39 is:

- inverted
- diminished.

Drawing ray diagrams for lenses

Figure P4.40 shows how the rays of light from a motorcycle can be converged by a lens to form an image of the motorcycle.

We can explain how this image is formed using a ray diagram. Ray diagrams are drawn to scale and show the path of two particular rays. The steps needed to draw an accurate ray diagram are shown in Worked example P4.04. Remember that it helps to work on squared paper or graph paper when drawing a ray diagram.

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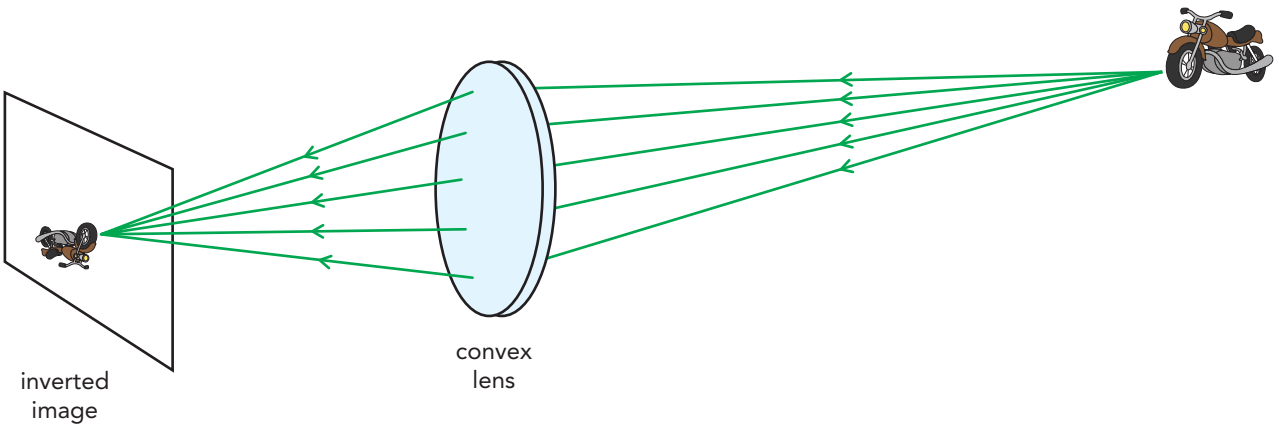
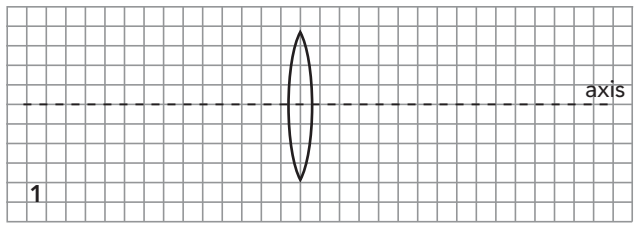


Figure P4.40: The rays of light from the motorcycle are converged by the lens to form a diminished, inverted image on the screen. This is how an image is formed in our eyes, or in a camera.

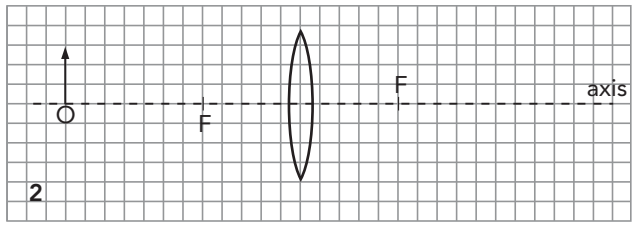
WORKED EXAMPLE P4.04

Draw a ray diagram to find the image formed of a 3 cm tall object placed 12 cm from a converging lens which has a focal length of 5 cm.

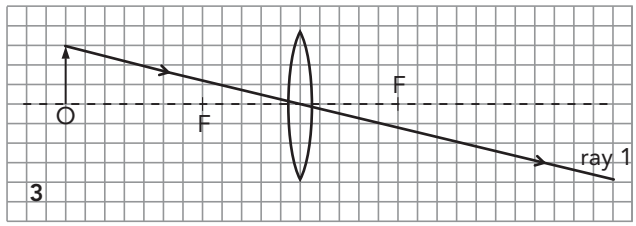
Step 1: Draw the lens (a simple outline shape will do) with a horizontal axis through the middle of it.



Step 2: Mark the positions of the principal focus (F) on either side, at 5 cm from the centre of the lens. Mark the position of the object, O, along with a 3 cm arrow standing on the axis. Place the arrow 12 cm from the lens.



Step 3: Draw ray 1, a straight line from the top of the object arrow which passes undeflected through the middle of the lens.



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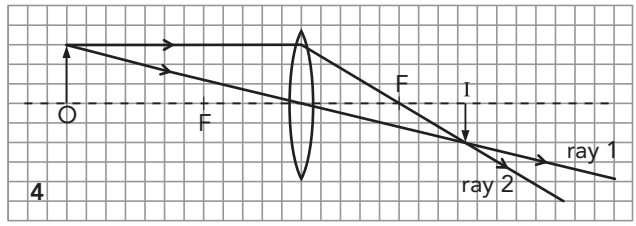
CONTINUED

Step 4: Draw ray 2 from the top of the object arrow parallel to the principal axis. As it passes through the lens, it is refracted through the principal focus. To make things easier when we draw ray diagrams, we only show rays bending once, at the centre of the lens.



Look for the point where the two rays cross. This is the position of the top of the image (I).

With an accurately drawn ray diagram, you can see that the image is inverted, diminished and real.

So, to construct a ray diagram like this, draw two rays starting from the top of the object:

- ray 1: unrefracted through the centre of the lens
- ray 2: parallel to the axis and then refracted through the principal focus.

ACTIVITY P4.04

Ray diagrams

Imagine you work for a company which makes cameras and projectors. You have been asked to produce short, technical guides explaining the use of lenses in these products.

Drawing ray diagrams lets us predict what an image will look like. A lens can make different images depending on its position. Draw the following ray diagrams:

- A lens with a focal length of 3 cm with the object 8 cm from the lens.
- The same lens but with the object 5 cm from the lens.

Describe the image formed in each case. Which is for a camera, and which for a film projector?

Draw diagrams to investigate the difference the thickness of a lens makes to the image. Remember, a fat lens has a short focal length, a thin lens has a longer focal length.

Peer assessment

Swap ray diagrams with a partner and check if they are correctly drawn.

Give them a smiley face, straight face or sad face for each of the following features:

- axis drawn horizontally through the middle of the lens
- focal point, F, marked on each side of the lens
- ray from the top of the object passing though the centre of the lens without being deflected

CONTINUED

- ray from the top of the object parallel to the axis striking the lens then passing through the principal focus
- rays drawn as straight lines using a ruler
- correct arrows on both rays
- image clearly marked, including which way up it is.

Discuss what, if anything, was missing and how you can both improve your diagrams.

Questions

P4.24 Copy and complete these sentences:

A converging lens refracts parallel rays of light to a point called the _____.

The distance from this point to the lens is called the _____.

The fatter the lens the _____ this distance will be.

P4.25 Copy and complete the ray diagrams in Figure P4.41 to show what happens when the rays hit the lenses.

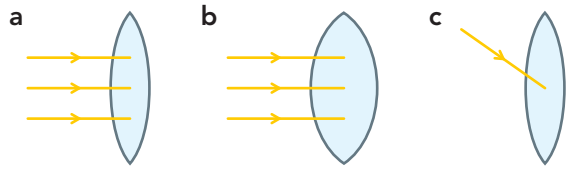


Figure P4.41: Ray diagrams.

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Magnifying glasses

A magnifying glass is a converging lens. You hold it close to a small object and peer through it to see a magnified image. Figure P4.42 shows how a magnifying glass can help to magnify print for someone with poor eyesight.

Figure P4.42: A converging lens produces a magnified image, making small print easier to read.

The object viewed by a magnifying glass is closer to the lens than the principal focus. We can draw a ray diagram using two rays.

- Ray 1 is unrefracted as it passes through the centre of the lens.
- Ray 2 starts off parallel to the axis and is refracted by the lens so that it passes through the principal focus.

Rays 1 and 2 do not cross over each other. They are diverging (spreading apart) after they have passed through the lens. Our eye assumes the rays have travelled in straight lines, as shown by the dashed lines. We see the image at point I, where the rays meet. We cannot catch the image on a screen, because there is no light there.

From the ray diagram (Figure P4.43), we can see that the image produced by a magnifying glass is:

- upright
- enlarged
- further from the lens than the object
- virtual.

So, if you read a page of a book using a magnifying glass, the image you are looking at is behind the page that you are reading. This image is a virtual image. The image formed in Worked example P4.04 is formed by real rays and can be seen on a screen, and is therefore called a real image.

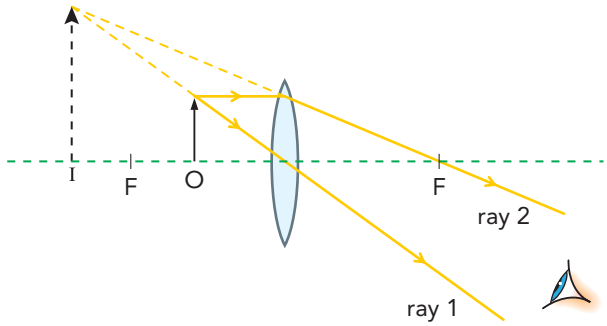

Figure P4.43: A ray diagram to show how a magnifying glass works. The object is between the lens and the focus. The image produced is virtual. To find its position, the rays have to be extrapolated back (dashed lines) to the point where they cross.

Dispersion of light

When white light passes through glass, it refracts as it enters and leaves the glass, and can be split into a **spectrum** of colours. Figure P4.44a shows light being refracted as it passes through a glass prism. You can see that the colours merge into one another. A rainbow (Figure P4.44b) is a naturally occurring spectrum. White light from the Sun is split up into a spectrum of colours as it enters and leaves droplets of water in the air.

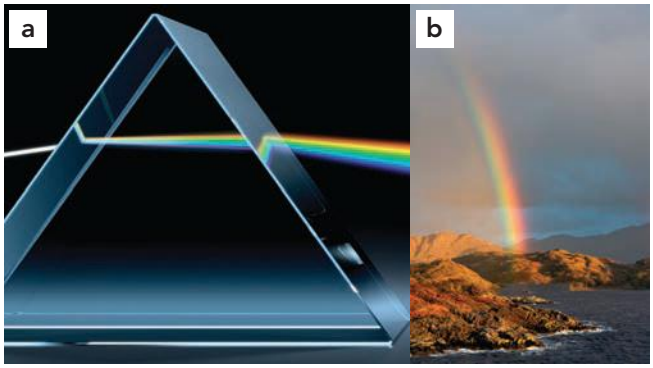

Figure P4.44 a: White light is dispersed by a prism.
b: Raindrops take the place of the prism to form a rainbow.

KEY WORD

spectrum: waves, or colours, of light, separated out in order according to their wavelengths.

The colours of the spectrum, in order, are:

Red – Orange – Yellow – Green – Blue – Indigo – Violet

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This splitting up of white light into a spectrum is known as **dispersion**.

As the white light enters the prism, it slows down. It is refracted and its direction changes. The amount each colour is refracted is different because their wavelengths and frequencies are different (Figure P4.45). Red light has the longest wavelength and the lowest frequency. Red is refracted least. Violet has the shortest wavelength and the highest frequency. Violet is refracted most.

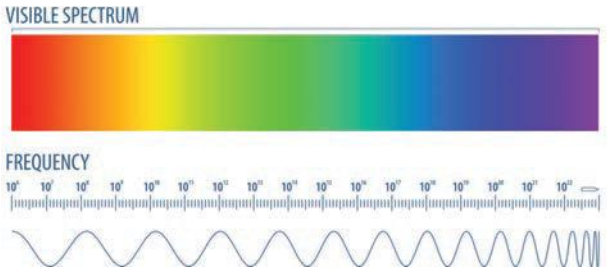

Figure P4.45: Different colours of light have different wavelengths. The longer the wavelength the less the light is refracted.

KEY WORD

dispersion: the separation of different wavelengths of light because they are refracted through different angles.

Questions

P4.26 Copy and complete these sentences.

When light enters glass it slows down, causing it to change direction. This is called _____.

Red light changes direction _____ than violet light.

The light is split into different colours. This is called _____.

P4.27 Draw a diagram to show how white light can be dispersed into a spectrum using a glass prism. Label the red and violet light.

P4.28 List the colours of the visible spectrum in order starting with the colour which is refracted the least.

REFLECTION

When we study light, we use very similar words and diagrams for reflection and refraction. Have you found this difficult? How have you learnt the rules for ray diagrams? How successful have you been?

P4.03 Electromagnetic spectrum

The visible spectrum is just a part of a larger spectrum known as the *electromagnetic spectrum*. There are waves with wavelength longer than red light, or shorter than violet light. We do not see these waves because our eyes are not adapted to detect them. However, we can detect them in other ways, such as by using infrared cameras. The waves have different properties and many are very useful to us, though some can also be dangerous.

Electromagnetic waves all have similar properties:

- They are all transverse waves which transfer energy.
- They can be reflected and refracted.
- They can all travel through a vacuum, and travel at the same speed in a vacuum.

The speed of all electromagnetic waves in a vacuum is the speed of light – 300 million metres per second (3×10^8 m/s).

The speed of electromagnetic waves in air is approximately the same as in a vacuum.

Figure P4.46 shows the complete electromagnetic spectrum, with the wavelengths and frequencies of each region.

Questions

P4.29 Draw and label *two* waves to show the difference between red light and violet light.

P4.30 Write the names of the waves in the electromagnetic spectrum:

a in order of increasing wavelength

b in order of increasing frequency.

P4.31 Use the equation $v = f\lambda$ to calculate the frequency of green light which has a wavelength of 540 nm.

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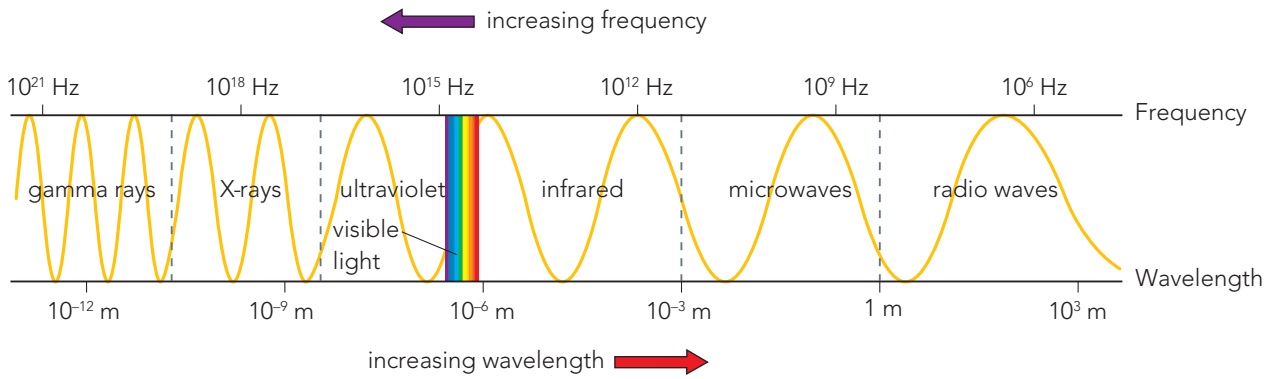

Figure P4.46: The electromagnetic spectrum.

REFLECTION

There are two spectra which you need to remember in order: visible light and the electromagnetic spectrum. How easily can you remember them? What helps you with this? Mnemonics can be very useful here. The colours of the visible spectrum can be remembered using Richard Of York Gave Battle In Vain. The first letters of the words correspond to the first letters of the colours. Try to make a mnemonic to remember the order of the waves in the electromagnetic spectrum.

Uses of electromagnetic waves

The different frequencies of the waves in the electromagnetic spectrum give them different properties and this means that they are useful in different ways. Here are some important examples.

Radio waves

Radio waves are used to broadcast radio and television signals. These waves are sent out from a transmitter a few kilometres away to be captured by an aerial on the roof of a house.

Radio waves are also used in radar systems to help ships navigate, or to measure the speed of vehicles (Figure P4.47).

Figure P4.47: Radio waves are emitted, reflected by a moving vehicle and detected in order to determine the speed of the vehicle.

Microwaves

Microwaves are used in satellite television broadcasting, because they pass easily through the Earth's atmosphere (Figure P4.48). They travel up to a broadcasting satellite, thousands of kilometres away in space. Then they are sent back down to subscribers on Earth. Microwaves are also used to transmit mobile phone (cellphone) signals between masts, which may be up to 20 km apart.

Microwave ovens emit microwaves, which are absorbed by molecules in food, causing heating.

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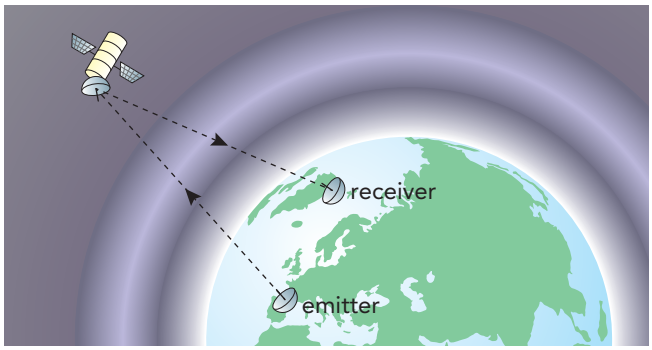

Figure P4.48: Microwaves allow signals to be transmitted around the curve of the Earth's surface.

Infrared

Infrared radiation is used in remote controls for devices such as televisions. A beam of radiation from the remote control carries a coded signal to the appliance, which changes the settings on the television; for example, changing channel or increasing the volume. You may be able to use a smartphone camera to observe this type of radiation, which would otherwise be invisible to our eyes. Point a remote control at your phone and record what happens as you press buttons. Grills and toasters also use infrared radiation to cook food. Security alarms send out beams of infrared radiation and detect changes in the reflected radiation, which may indicate the presence of an intruder. Infrared can also be used in medicine (Figure P4.49).

Figure P4.49: Using an infrared scanner allows a doctor to see a patient's veins. This means injections can be targeted much more precisely.

Visible light

Visible light provides us with information about the world, both directly through our eyes and via optical instruments such as cameras, telescopes and microscopes. Visible light is also vital for photosynthesis.

Ultraviolet (UV) light

UV light causes some chemicals to emit visible light. This includes body fluids such as sweat and saliva. Forensic scientists use this to find evidence at crime scenes which is invisible to the human eye. Chemicals which glow in UV light can be used for security marking of valuable equipment and banknotes (Figure P4.50).

Figure P4.50: Many banknotes have markings which are only visible in ultraviolet light. This helps in the detection of forged banknotes.

X-rays

X-rays can penetrate solid materials and so they are used in security scanners at airports. They are also used in hospitals and clinics to see inside patients without the need for surgery. The X-rays are detected using electronic detectors. Bone absorbs X-rays more strongly than flesh, so bones appear as a shadow in the image. Similarly, a metal gun will appear as a shadow because it absorbs X-rays more strongly than the items around it in Figure P4.51.

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Figure P4.51: X-ray scanners allow airport security to quickly detect hidden items.

Gamma rays

Gamma rays can be used both to detect and treat cancers. You will learn more about this in Chapter P8.

Questions

P4.32 Name *two* types of electromagnetic radiation that are used to cook food.

P4.33 Name *two* types of electromagnetic radiation that have medical uses.

P4.34 A girl phones her friend on her mobile phone while watching TV by a log fire. Explain how infrared radiation, microwaves, visible light and radio waves are involved in this.

P4.35 The radiographer must leave the room before operating an X-ray machine. Why is it considered too dangerous for the radiographer but not for the patient?

Electromagnetic hazards

All types of radiation can be hazardous. Even bright light shining into your eyes can blind you. Infrared radiation can cause burns. UV radiation from the Sun can damage skin cells which may lead to sunburn and skin cancer. Sunbeds can also damage skin cells and should be used with care.

UV radiation can also damage eye cells which is why it is important to protect your eyes in bright sunlight by wearing sunglasses or a hat. In general, the higher the frequency of the wavelength, the greater the harm it can cause.

X-rays and gamma rays are the most dangerous part of the electromagnetic spectrum. They can cause cell mutations which may lead to cancer. Medical professionals who work with X-rays are in danger of being exposed to too much radiation. They can protect themselves by standing well away, behind a screen, when a patient is being examined, or by enclosing the equipment in a metal case, which will absorb rays (Figure P4.52a and b).

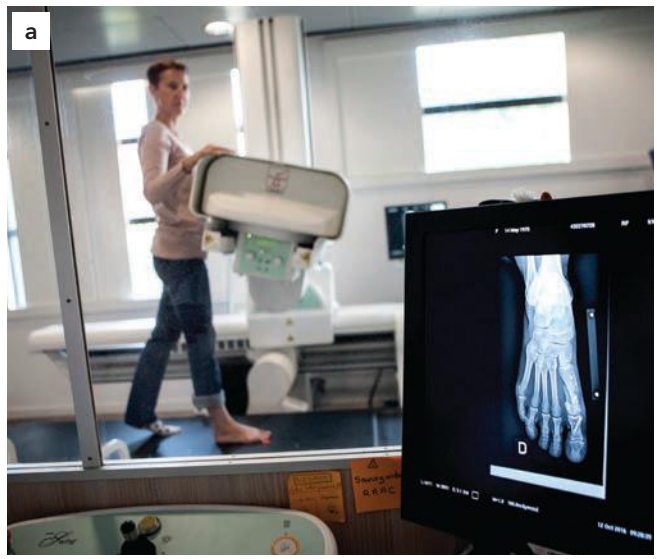

Figure P4.52 a: The radiographer operates the machine from a separate room. **b:** All areas where X-rays or gamma rays are used have hazard warning labels.

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ACTIVITY P4.05

Electromagnetic waves – friend or foe?

Each of the pictures in Figure P4.53 represents a use or a danger of a type of electromagnetic radiation. Identify the wave involved and discuss what the use or danger is.

Figure P4.53: Uses and dangers of electromagnetic radiation.

Find or draw as many pictures as you can showing the uses and dangers of electromagnetic waves.

Use your pictures to make a poster. Include a representation of the electromagnetic spectrum similar to Figure P4.46.

P4.04 Sound

Making sounds

All sounds are caused by something vibrating. The vibrations are not always visible because they may be too small or too fast. Vibrating sources cause the air around them to vibrate. These vibrations are passed through the air to our ears where they cause the eardrum to vibrate and we hear sound. Figure P4.54 shows how some vibrating objects create sound waves.

Questions

P4.36 What are all sounds caused by?

P4.37 A drum, a flute and a violin all play a note. For each instrument state what vibrates to create the sound.

P4.38 Describe how a drummer hitting a drum leads to a listener hearing sound.

Figure P4.54 a: Hitting the gong with a hammer causes the gong to vibrate. **b:** Djembe drums are made in a range of sizes to produce different notes. The skin vibrates when hit and produces sound waves. **c:** The water particles on this speaker are vibrating as the speaker makes a sound. The vibrations of the speaker and the water will change if the pitch or loudness of the sound is changed. **d:** The cicada has ribbed membranes at the base of its abdomen which vibrate, creating sound.

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More about sound waves

Sound waves are longitudinal waves. Figure P4.55a shows how a vibrating object such as a tuning fork creates compressions and rarefactions in the air, which travel through the air as a sound wave. The vibrations of the prongs are not easy to see, but their effect on water can be dramatic (Figure 4.55b).

Compressions are areas where the air particles have been squashed closer together, creating higher pressure. Rarefactions are the areas between the compressions where the pressure is lower as the particles are further apart.

What can sound travel through?

Sound waves are vibrations caused by particles moving back and forth. In a vacuum there are no particles, so it is impossible for sound to travel.

Sound needs a medium (material) to travel through. This can be shown in an experiment using a bell in a glass jar (Figure P4.56).

Sound can travel through solids. You may be able to hear sounds from outside the classroom as you read this. Sound vibrations can travel through the walls.

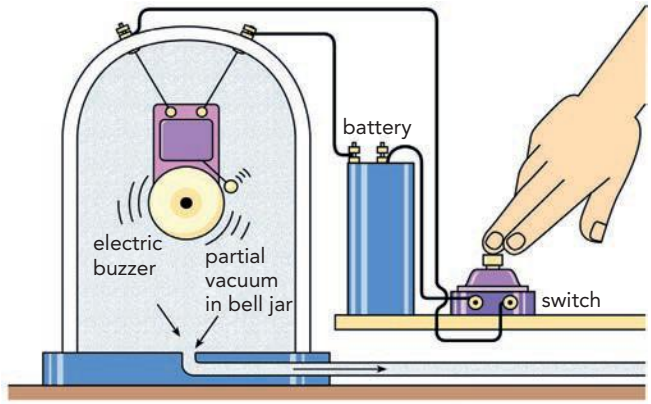

Figure P4.56: When the battery is connected, the bell can be seen and heard. Vibrations from the bell pass through the air in the jar, through the glass and then through the air to your ear. When the pump removes the air from the jar, creating a vacuum, the bell can still be seen vibrating, but cannot be heard.

Sounds can also pass through liquids. Many sea animals such as dolphins and whales use sound to communicate with each other and to navigate.

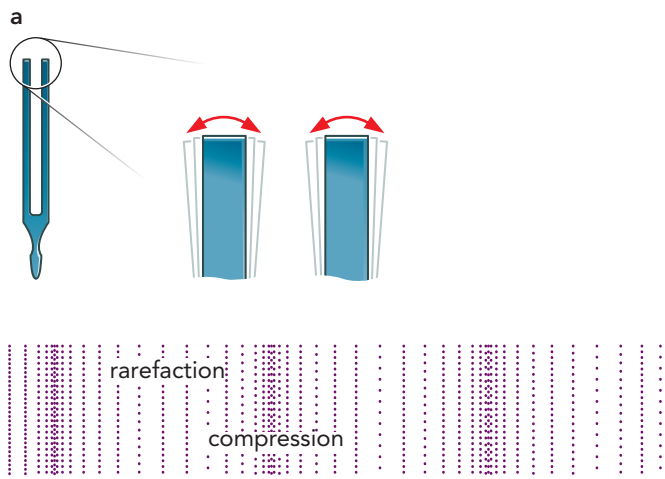

Figure P4.55 a: The tuning fork's prongs move back and forth creating compressions and rarefactions in the air. **b:** The number on the tuning fork tells us that the fork vibrates 440 times a second. It creates sound waves with a frequency of 440 Hz.

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Questions

P4.39 Why can't sound be heard in a vacuum?

P4.40 What is heard when the vacuum pump in Figure P4.56 is switched on?

The speed of sound

Sound travels at between 330 m/s and 350 m/s in air. The speed changes slightly depending on the temperature and humidity of the air. This is much slower than light, but still so fast that we are usually not aware of the time it takes for sounds to reach us, unless the distance it travels is large.

An echo is a reflected sound wave. If you bang two wooden blocks together in the classroom you will hear only one bang. The sound will reflect from the walls, but the echo will be so close to the original bang that you will not hear it as a separate sound. Banging the blocks outside will mean the sound has further to travel, so you may hear an echo. This can be used to measure the speed of sound.

EXPERIMENTAL SKILLS P4.03

Measuring the speed of sound in air

You can calculate the speed of sound in air by measuring the time taken for an echo to be heard.

You will need:

- 2 wooden blocks
- stopwatch
- long tape measure or trundle wheel.

Safety

You will be creating very loud sounds. Avoid doing this near anyone's ears as loud sounds can damage the ear.

Getting started

Why is it necessary to stand a long distance from the wall?

Why will it be difficult to measure the time from hitting the blocks together to hearing the echo?

Method

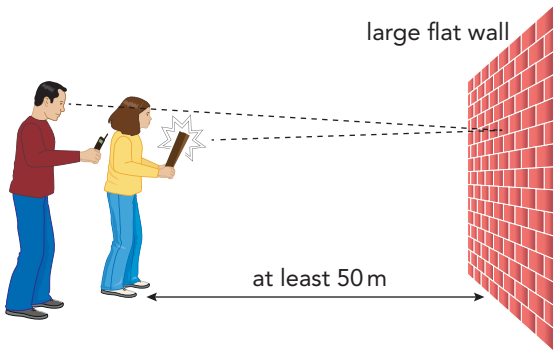

Figure P4.57: Measuring the speed of sound in air.

1. Stand a measured distance (ideally at least 50 metres) from a large flat wall. Bang the blocks together and listen for the echo (see Figure P4.57).
2. Now try to bang the blocks in an even rhythm so that each clap coincides with the echo of the previous bang. This will mean you do not hear the echo separately from the next bang. This may take some practice.
3. Your partner should then measure the time for 20 of your bangs.
4. Record the time taken for 20 bangs and the distance from the wall.
5. Calculate the total distance travelled by the sound. Each bang involves the sound travelling to the wall and back, so the total distance is 20 × 2 × distance from wall.
6. Calculate the speed of sound in air. Use the equation:

$$\text{speed} = \frac{\text{distance travelled}}{\text{time taken}}$$

Questions

1. What is the actual speed of sound in air? How does the value you calculated compare to this?
2. Which measurement (distance or time) do you think was least accurate? Explain your answer.

Reflection

Discuss the experiment with a partner. Suggest ways to improve your experiment to increase the accuracy of this measurement.

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A more precise value of the speed of sound can be obtained using an electronic timer and microphones. Figure P4.58 shows this method. The wooden blocks and the two microphones are arranged in a straight line.

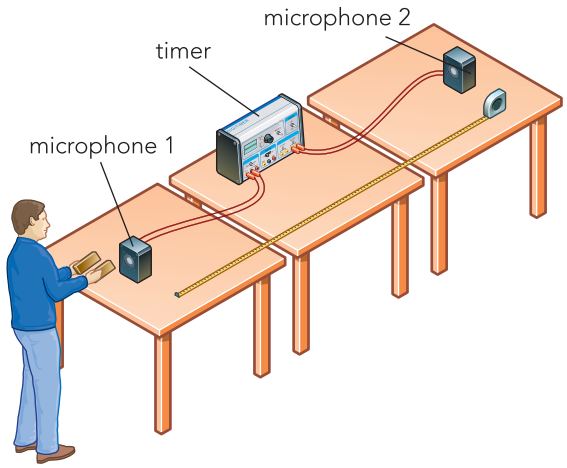

Figure P4.58: Another method for measuring the speed of sound.

When the student bangs the two blocks of wood together, it creates a sudden, loud sound. The sound reaches microphone 1 and a pulse of electric current is sent to the timer. The timer starts timing. A fraction of a second later the sound reaches microphone 2. A second pulse of current is sent to the timer and stops it. The timer now indicates the time it took for the sound to travel from microphone 1 to microphone 2. If the distance between the two microphones is measured, the speed of sound can be calculated using the equation:

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

WORKED EXAMPLE P4.05

A man blows a whistle and hears the echo from a rock face after 3.6 seconds. How far away from the rock is he? Assume speed of sound in air = 340 m/s.

Step 1: Calculate the distance travelled by the sound.

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

so, distance = speed × time

= 340 m/s × 3.6 s

= 1224 m

CONTINUED

Step 2: Halve this distance. (The distance you have already calculated is the total distance travelled by the sound, to the rock face and back. The distance to the rock face is half of this.)

$$\frac{1224}{2} = 612\,\text{m}$$

Answer

The rock face is 612 metres away from the man.

Sound travels at different speeds in different materials. Figure P4.59 shows the speed in different materials. This can be explained by considering the spacing of particles. Particles are closer together in solids than in liquids, so the vibrations can be passed on more easily in solids. This means that the sound wave travels fastest in a solid and slowest in a gas.

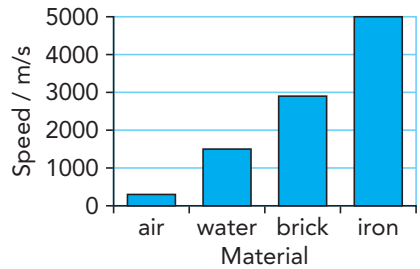

Figure P4.59: The speed of sound in different materials.

Questions

P4.41 A spectator at a cricket match sees the batsman hit the ball, then 1.2 seconds later he hears the strike. How far away is the spectator? The speed of sound in air is 330 m/s.

P4.42 Explain why the method shown in Figure P4.58 is more accurate than the echo method when measuring the speed of sound.

Seeing and hearing sounds

Seeing sounds

A cathode ray oscilloscope and microphone can be used to represent sounds on a display screen (Figure P4.60). The microphone picks up the sound and converts it to an electrical signal. The oscilloscope converts this to a line which represents the vibrations that make up the sound wave.

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The vibration from a musical instrument is complicated because it is produced by vibrations of the air and the instrument itself. A signal generator can be used to produce a pure sound wave. Pure notes are easier to measure, but not so musical.

Figure P4.60: As the student blows, he creates vibrations in the air. The vibrations are detected by the microphone and converted to electrical signals, which are displayed on the oscilloscope.

The oscilloscope trace that represents a pure note is a simple curve as shown in Figure P4.61a. When representing a musical note from a particular musical instrument, the pattern is more complicated. Figures P4.61b and P4.61c show this.

The oscilloscope can be used to observe two important things about the wave (Figure P4.62).

- The amplitude is the furthest distance the particles move from their undisturbed position. This is shown by the height or depth of the oscilloscope trace.
- The frequency is the number of vibrations each second. The more waves on the screen, the higher the frequency. Frequency is measured in hertz. One hertz means one wave per second.

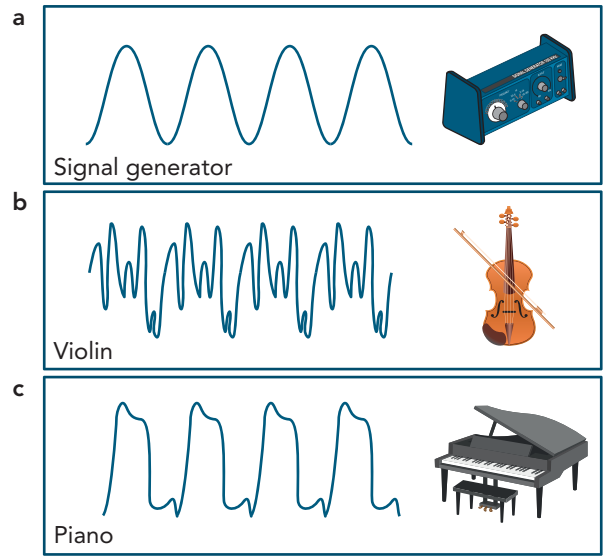

Figure P4.61: The three representations of sound waves shown here are all the same note. Each wave has a repeating pattern. The design of the instrument adds extra vibrations called overtones which give each instrument its distinctive sound. All three waves have four repeats, meaning that they all are the same note.

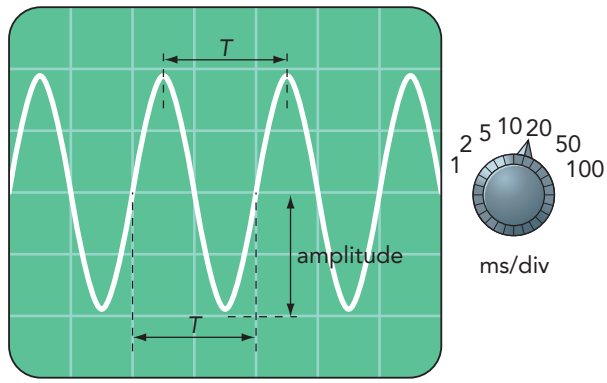

Figure P4.62: The frequency of the note can be calculated from the oscilloscope trace. This oscilloscope is set at 20 ms/div. This means each division on the grid represents 20 ms (0.02 s). The time for one wave (marked as T) is two divisions or 0.04 seconds. One wave takes 0.04 seconds, so the number of waves each second is 1 ÷ 0.04 = 25 Hz.

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Connecting a signal generator and a speaker to an oscilloscope allows you to both see a representation of the sound wave and hear the sound.

Increasing the loudness of the sound produces taller waves – they have a bigger amplitude. Increasing the frequency means more waves will be seen on the screen – they have a higher frequency, and the sound heard will be higher pitched. Remember:

- high frequency means high pitch, low frequency means low pitch
- large amplitude means loud sound, small amplitude means quiet sound.

Hearing sounds

Young humans can hear sounds from 20 Hz up to 20 000 Hz. As we grow older, the sensory cells in the ear which detect vibrations deteriorate. This means that the range of sounds which can be heard decreases with age. These cells can also be damaged by repeated exposure to very loud noise.

Sound waves with a frequency above 20 000 Hz cannot be heard by humans. Sound waves above 20 000 Hz are called **ultrasound**. Ultrasound is used in some medical procedures such as scans on developing fetuses (Figure P4.63).

Figure P4.63: An ultrasound scan gives a clear image of the developing fetus, but unlike an X-ray this procedure does not carry any risk.

KEY WORD

ultrasound: any sound with a frequency higher than 20 000 Hz.

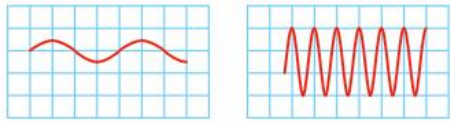
Question

P4.43

a What is meant by the term 'frequency of a sound'?

b What units is frequency measured in?

c Figure P4.64 shows the traces produced on an oscilloscope by two different sounds. Describe *two* ways in which sound B is different from sound A.

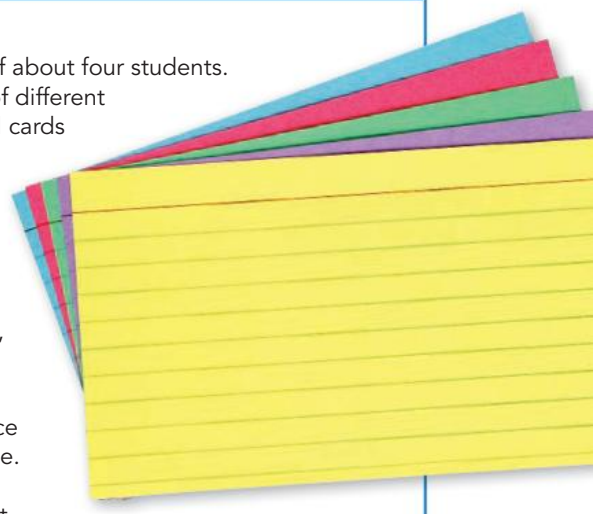


Sound A Sound B

Figure P4.64: Oscilloscope traces for two different sound waves.

ACTIVITY P4.06

Guess who?



Work in a group of about four students. Write the names of different waves on identical cards (radio waves, microwaves, infrared, visible light, ultraviolet, X-rays, gamma rays, red light, violet light, sound, ultrasound and water waves).

Place the cards face down in the middle. One player takes a card and looks at it without letting the others see. The other players then try to find out what the wave is by asking questions to which the answer can only be 'yes' or 'no'. For example, 'Are you longitudinal?' Each player can only ask one question.

When the wave has been identified, the next player takes their turn.

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PROJECT P4.01 SO, WHAT IS A WAVE?

You work for a television company that is making a programme about the discovery of gravitational waves. The producer has asked your team to work on a five-minute introduction to the general idea of waves. You need to answer the question: 'What is a wave?'.

The director thinks viewers may think of waves as being just water waves. She wants viewers to have a clear idea of what a wave is and how waves behave. Viewers should understand why physicists describe light and sound as waves.

You will need to show that water, light and sound waves behave in the same ways, particularly that they can be reflected, refracted and diffracted.

You should also explain some of the differences, for example, that sound waves need a medium.

Your section will introduce the programme, so it needs to get the audience's interest so they do not reach for the remote control. (You could point out that the remote control is operated by infrared or radio waves!) The producer suggests you might show a crowd doing a Mexican wave as a way of showing energy being transferred by a wave. You could also include pictures or video clips of water waves, including seismic waves and tsunamis.

Once you have the audience interested, you will need to introduce the idea that waves transmit energy but not matter. Illustrate this by referring to waves in springs, boats bobbing on the waves at sea, or any other examples you can think of. You should then cover wave behaviour, giving as many examples as possible to show the audience how many everyday things depend on waves.

You may present your ideas as a video, or as a storyboard.

When the programme is broadcast all your names will be in the credits, along with your job title. Decide early on what each person will do. Jobs could include: researcher, picture researcher, editor, producer, sound technician, cameraperson and any other roles you think are needed.

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SUMMARY

Waves transfer energy without transferring matter.
Waves can be transverse or longitudinal.
Waves can be described in terms of their wavelength, amplitude, frequency and wave speed.
Wave speed, frequency and wavelength are related by the equation $v = f\lambda$
Waves can be reflected and refracted.
Waves can be diffracted when they pass through a gap. Diffraction is greatest when the gap is about the same size as the wavelength of the wave.
The law of reflection: angle of incidence = angle of reflection.
The image in a plane mirror is upright, as far behind the mirror as the object is in front and swapped round left to right.
The image in a plane mirror is virtual.
Refraction is the bending of light as it goes from one substance to another.
Refraction is caused by light travelling at different speeds in different materials.
When light passes from air to glass it bends towards the normal. When it passes from glass to air it bends away from the normal.
Converging lenses bend parallel rays together so they meet at a point called the principal focus.
Drawing a ray parallel to the axis, and a ray which strikes the centre of a lens allows us to draw a ray diagram and find the type of image formed.
A magnifying glass produces a virtual image.
When the angle of incidence in glass is equal to, or greater than, the critical angle, all the light is reflected back into the glass. This is total internal reflection.
The refractive index is a measure of how much light is slowed, or bent, by a material.
Refractive index can be calculated using the equation $n = \frac{\sin i}{\sin r}$
Optical fibres can transmit information rapidly and efficiently using total internal reflection. This is useful in telecommunications and medicine.
White light can be dispersed by passing it through a glass prism. This creates the visible spectrum. The colours of the spectrum are red, orange, yellow, green, blue, indigo, violet.
The electromagnetic spectrum is a group of waves which have similar properties to light.
In order of increasing frequency, the waves in the electromagnetic spectrum are: radio waves, microwaves, infrared, visible light, ultraviolet, X-rays and gamma rays.

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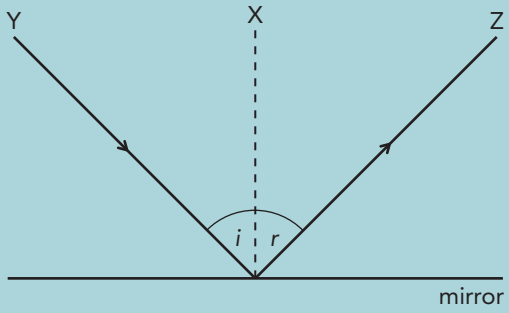
CONTINUED

All electromagnetic waves travel at the same speed – the speed of light.
The speed of light is 300 000 000 m/s.
Electromagnetic waves have different wavelengths and this gives them different properties and makes them suitable for different uses.
High frequency electromagnetic radiation can be hazardous. It can damage cells and cause cells to mutate.
All sounds are caused by vibrating sources.
Sound waves are longitudinal waves.
Sound waves consist of a series of compressions and rarefactions.
Sound waves need a medium to travel through.
Sound travels fastest in solids and slowest in gases.
An echo is a reflected sound.
The greater the amplitude of a sound, the louder the sound.
The greater the frequency of a sound, the higher its pitch.
Humans can hear sounds between 20 Hz and 20 000 Hz.

PRACTICE QUESTIONS

1 The diagram shows a ray of light striking a plane mirror.



Identify which row gives the correct labels for the diagram.

	X	Y	Z
A	normal	incident ray	angle of refraction
B	angle of incidence	incident ray	normal
C	reflected ray	normal	angle of reflection
D	normal	incident ray	reflected ray

[1]

COMMAND WORD

identify: name/select/recognise.

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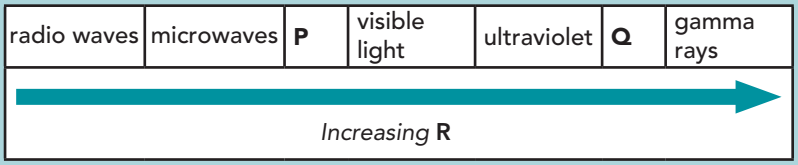
CONTINUED

2 Identify which option best describes what is transferred by a wave.

A energy and matter **B** just energy

C just matter **D** neither energy nor matter **[1]**

3 This is part of the electromagnetic spectrum:



a Identify the waves labelled **P** and **Q**. **[2]**

b **State** whether **R** represents frequency or wavelength. **[1]**

[Total: 3]

4 **a** **Define** *frequency of a sound*. **[1]**

b State the units used to measure frequency. **[1]**

c State the name given to sounds with a frequency of more than 20 000 Hz. **[1]**

[Total: 3]

5 A student sees a flash of lightning and, three seconds later, she hears the thunder.

a **Suggest** why she sees the lightning before she hears the thunder. **[1]**

b Light and sound are both types of waves.

Copy and complete the following sentences. Choose from this list of words:

transverse **longitudinal** **parallel to**

at right angles to **can** **cannot**

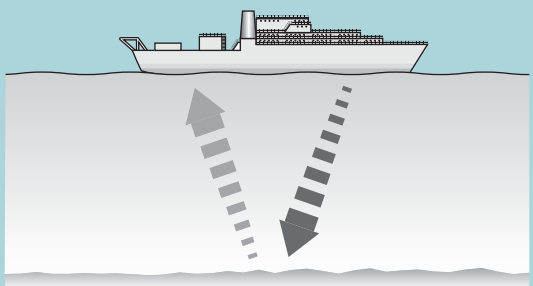
i Light is a _____ wave. The vibrations are _____ the direction of travel of the wave. These waves _____ travel through a vacuum. **[3]**

ii Sound is a _____ wave. The vibrations are _____ the direction of travel of the wave. These waves _____ travel through a vacuum. **[3]**

c The speed of sound in air is 330 m/s. **Calculate** how far away the storm is from the student. **[2]**

[Total: 9]

6 A ship uses echo sounding to find the depth of the water. It sends out an ultrasound pulse and detects the echo after three seconds.



COMMAND WORDS

state: express in clear terms.

define: give a precise meaning.

suggest: apply knowledge and understanding to situations where there is a range of valid responses in order to make proposals/put forward considerations.

COMMAND WORD

calculate: work out from given facts, figures or information.

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CONTINUED

a Calculate the depth of the water. Assume that the speed of sound in water is 1500 m/s. **[2]**

b The ship's siren is heard by a boy windsurfing nearby. He is 400 metres away from the boat. Calculate how long it will take the sound to reach him. Assume that the speed of sound in air is 340 m/s. **[2]**

c The sound of the siren also travels through the metal body of the ship. **Determine** which of the following could be the speed of sound in the steel.

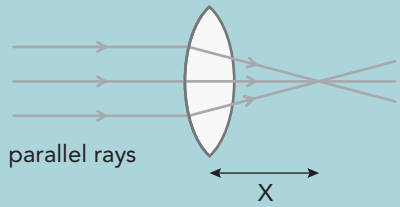
200 m/s

1200 m/s

5800 m/s **[1]**

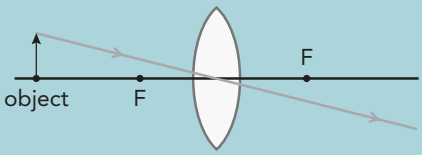
[Total: 5]

7 This diagram shows light being refracted by a converging lens.



a State the name given to the distance marked X. **[1]**

b This diagram shows one ray of light passing through the lens. The lens can be used to form an image of an object.



Copy the diagram and draw another ray to complete it. Add an arrow to represent the image. **[3]**

c Choose *two* of these words to describe the image in **b**. **[2]**

upright **inverted** **diminished** **enlarged**

[Total: 6]

COMMAND WORD

determine: establish an answer using the information available.

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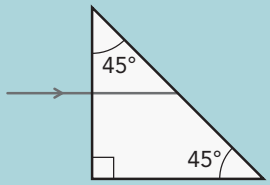
CONTINUED

8 This diagram shows a ray of light entering a glass prism.
The critical angle of the glass is 42°.



a **Explain** why the ray is not refracted as it enters the glass. **[1]**

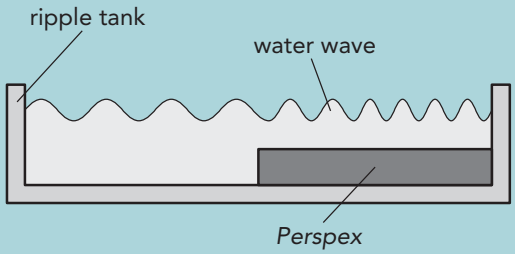
b Copy and complete the diagram to show what happens to the ray. **[1]**

c **Give** the name of the effect you have drawn. **[1]**

d If the prism was removed, suggest what other piece of apparatus could produce the same effect on the light ray. **[1]**

[Total: 4]

9 The diagram shows waves going from deep water into shallower water above a *Perspex* block.



Describe what happens to each of the following when the wave enters the shallower water:

a wavelength **[1]**

b wave speed **[1]**

c frequency **[1]**

d amplitude. **[1]**

[Total: 4]

10 Radio station A broadcasts radio waves with a wavelength of 1500 metres and a frequency of 200 kHz. Station B has a frequency of 100 MHz.

a Calculate the speed at which the waves travel. **[1]**

b Use your answer to part **a** to calculate the wavelength of the waves from station B. **[1]**

[Total: 2]

COMMAND WORDS

explain: set out purposes or reasons/make the relationships between things clear/say why and/or how and support with relevant evidence.

give: produce an answer from a given source or recall/memory.

COMMAND WORD

describe: state the points of a topic/give characteristics and main features.

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SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
state what is transferred by a wave	P4.01			
illustrate wave motion using ropes, springs and water waves	P4.01			
define and use the terms: wavelength, frequency, amplitude, wave speed, crest, trough, compression, rarefaction	P4.01			
recall and use the equation linking wave speed, frequency and wavelength	P4.01			
describe and give examples of transverse and longitudinal waves	P4.01			
draw diagrams to show reflection and refraction of waves in a ripple tank	P4.01			
draw diagrams to show diffraction of waves in a ripple tank	P4.01			
describe how an image is formed in a plane mirror	P4.02			
recall and use the equation: angle of incidence = angle of reflection	P4.02			
draw a ray diagram to show the formation of an image in a plane mirror	P4.02			
describe an experiment to investigate how light is refracted when it passes through a glass block	P4.02			
recall and use the equation: $n = \frac{\sin i}{\sin r}$	P4.02			
draw a labelled diagram of light passing through a glass block, labelling the normal and the angles of incidence and refraction	P4.02			
describe and explain how total internal reflection is used in telecommunications and medicine	P4.02			
draw a fully labelled ray diagram to show the formation of a real image by a converging lens	P4.02			
draw a fully labelled ray diagram to show the formation of a virtual image by a converging lens and explain how this is used in a magnifying glass	P4.02			

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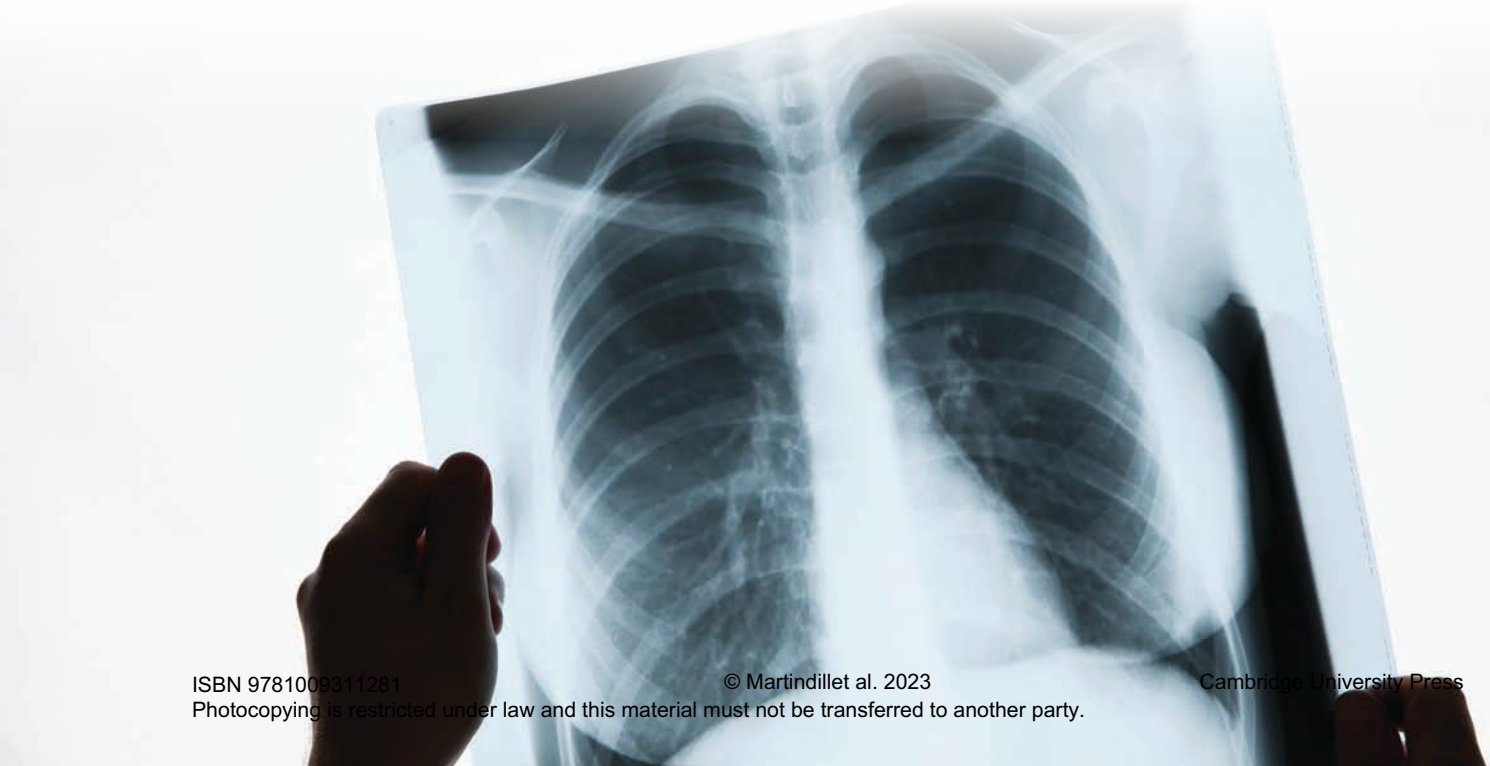
CONTINUED

I can	See topic . . .	Needs more work	Almost there	Confident to move on
describe internal reflection and recall that if the angle of incidence is greater than the critical angle, total internal reflection occurs	P4.02			
name the seven colours of the visible spectrum in the correct order	P4.02			
describe the properties all electromagnetic waves share	P4.03			
list the waves in the electromagnetic spectrum in order of increasing frequency or wavelength	P4.03			
state the speed of electromagnetic waves in a vacuum	P4.03			
describe uses and dangers of the waves in the electromagnetic spectrum	P4.03			
describe how sounds are produced	P4.04			
state that sound needs a medium	P4.04			
describe a method to measure the speed of sound in air	P4.04			
compare the speed of sound in solids, liquids and gases	P4.04			
describe how the amplitude of a sound affects its loudness.	P4.04			
describe how the frequency of a sound affects its pitch	P4.04			
explain how an echo is made	P4.04			
define the term ‘ultrasound’	P4.04			
state the range of sounds which humans can hear.	P4.04			



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P5

Electricity and magnetism

All learners study some content in this chapter

IN THIS CHAPTER YOU WILL:

- investigate the forces between positive and negative electric charges
- distinguish between electrical conductors and insulators
- understand how current, resistance and voltage are related
- calculate electric current, potential difference and resistance
- learn how the resistance of a wire relates to its length and diameter
- understand that energy is transferred from the power source (for example, a battery) to the circuit components
- calculate electrical power and energy
- describe magnetic forces between magnets, and between magnets and magnetic materials
- distinguish between the magnetic properties of soft iron and steel
- distinguish between the design and use of permanent magnets and electromagnets
- describe what is meant by a magnetic field
- describe induced magnetism
- explain static charge in terms of gaining or losing electrons
- describe what is meant by an electric field.

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BEFORE YOU START

In a small group, discuss what you know about electricity and magnetism. Organise your ideas into a mind map. Include as many of the following words as possible, giving definitions and examples wherever you can: magnet, magnetic field, electron, charge, current, static electricity, shock, voltage, conductor, insulator.

One member of the group should now stay with the map to explain it to other groups. The rest of the group should visit the maps of different groups. Having done this, return to your own group and add any additional information to your map.

SCIENCE IN CONTEXT P5.01

A shocking phenomenon

Figure P5.01 a: Lightning and electrical sparks are both caused by a large build-up of electric charge. **b:** Electrical hazard symbol.

The similarity between lightning bolts and the sign used for electrical hazards is not a coincidence (Figure P5.01). A large build-up of electrical charge can cause the air to break down and conduct electricity, potentially delivering a fatal electric shock. In December 2014, a potential difference of 1.3 billion volts was recorded during a thunderstorm over Ooty in Southern India.

The US scientist Benjamin Franklin was lucky to survive his experiments into this kind of electricity. He suspected lightning was a form of electricity due to the similarity between a lightning flash and the sparks he produced in his laboratory. To investigate he flew a kite into a thundercloud. To avoid being electrocuted, he included a metal key at the bottom of the kite string, and attached a length of ribbon to the key. Holding the ribbon, he was relatively safe from electrocution (although other people were killed when they repeated his experiment). As a bolt of lightning struck the kite, Franklin saw the fibres of the kite string stand on end and a spark jumped from the key to the ground.

Franklin's method was hazardous, and by flying a kite into the cloud, he may have brought on a lightning flash and thereby affected the situation he was investigating. Sunil Gupta and the team who measured the potential difference in the Ooty storm used a rather different method. They studied muons – a type of subatomic particle – as they passed through the storm cloud. The muons gained energy from the potential difference in the cloud, increasing the number which reached the scientists' muon sensors. This allowed the team to calculate the potential difference within the cloud.

Discussion questions

1 Franklin made important discoveries about static electricity, but his experiment would be considered too dangerous to be carried out now. Should scientists be allowed to conduct hazardous investigations?

2 Gupta's observations did not affect the situation he was studying. Why is this an important feature of scientific research?

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P5.01 Electric charge

Charging and discharging

A charged object may attract uncharged objects. Figure P5.02 shows one way of investigating how charged objects affect each other. A plastic rod is rubbed with a cloth so that both become charged. The rod is hung in a cradle so that it is free to move. When the cloth is brought close to it, the rod moves towards the cloth (Figure P5.02a). When a second rod is rubbed in the same way and brought close to the first one, the hanging rod moves away (Figure P5.02b). Charged objects can either attract or repel each other. This suggests that there are two types of static electricity. Both rods have been treated in the same way, so they will have the same type of electricity. The cloth and the rod must have different types.

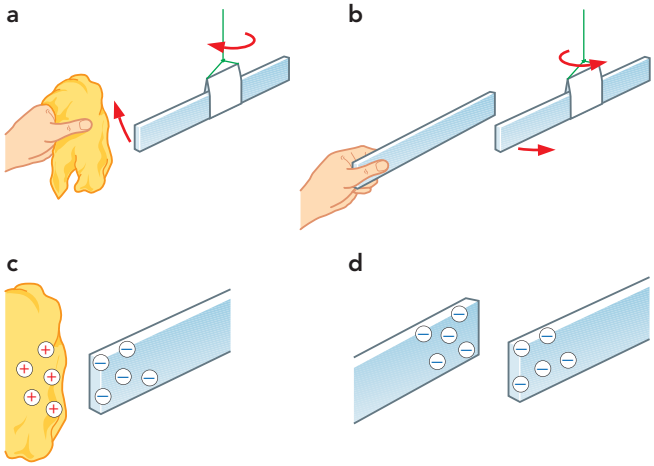

Figure P5.02: Two experiments to show the existence of two, opposite, types of electrical charge. **a:** The charged rod and cloth attract one another. **b:** The two charged rods repel one another. **c:** The rod and the cloth have opposite electric charges. **d:** The two rods have the same type of electric charge.

There are two types of static electricity, called **positive charge** and **negative charge**. We can explain the experiments shown in Figure P5.02 by saying that the process of rubbing gives the rods one type of electric charge (say, negative), while the cloth is given the opposite type (say, positive). Figures P5.02c and P5.02d show the two experiments with the charges marked.

KEY WORDS

positive charge: the type of electric charge carried in the nucleus of an atom.

negative charge: the type of electric charge carried by electrons.

From these experiments, we can describe the forces that electric charges exert on each other:

- Two positive charges will repel each other.
- Two negative charges will repel each other.
- A positive charge and a negative charge attract each other.

Questions

P5.01 Copy and complete these sentences.

There are two types of charge called _____ and _____.

Two objects with the same charge will _____ and two objects with opposite charges will _____.

P5.02 Figure P5.03 shows a child's hair standing on end after the child has been on a trampoline.

Figure P5.03: Friction can cause hairs to become charged. The hairs will have the same charge as each other and so will repel each other.

a How does bouncing on the trampoline cause the child's hair to become charged?

b The individual hairs are repelling each other. What does this tell you?

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The wires we use to connect circuits are made of metal because metals are good conductors of electric currents. Conductors allow electrical charge to flow through them, insulators don't allow charge to move. The metal is usually surrounded by plastic so that, if two wires touch, the electric current cannot pass directly from one to another (causing a short circuit).

Some non-metals conduct a little. For example, if you receive an electric shock, electrical charge flows through your body.

P5.02 Current, voltage and resistance

Electric current

When a circuit is complete, an electric **current** flows. A current is a flow of electric charge. In a metal, the current is a flow of electrons. Current flows from the positive terminal of the supply, around the circuit, and back to the negative terminal.

A current that flows in the same direction all the time is called **direct current (d.c.)**. **Cells** and **batteries** produce d.c.

Generators produce **alternating current (a.c.)**. An alternating current periodically reverses direction. In many countries, mains electricity has a frequency of 50 Hz. This means it changes direction 100 times per second.

The rest of this chapter, and Chapter P6, will consider only direct current.

Two pictures: current and electrons

Metals are good electrical conductors because they contain some electrons that can move about freely as they are not attached to atoms. These are known as delocalised or mobile electrons. A voltage, such as that provided by a battery or power supply, can make these electrons move, creating a current. Since electrons have a negative electric **charge**, they are attracted to the positive terminal of the battery. Electrons flow from negative to positive.

In the early days of circuits, scientists knew something was flowing from one side of the cell, round the circuit, and back to the cell. They had no way of knowing which type of charge moved, so they described positive charge flowing from positive to negative. The discovery of the electron showed this was wrong and that the flow is actually negative electrons flowing from negative to positive.

Unfortunately for physics students, the idea of positive charge flowing from positive to negative was kept and this current was called **conventional current**. You need to remember:

- Conventional current flows from positive to negative.
- Electrons flow from negative to positive.

So, we have two different pictures of what is going on in a circuit, as Figure P5.04 shows.

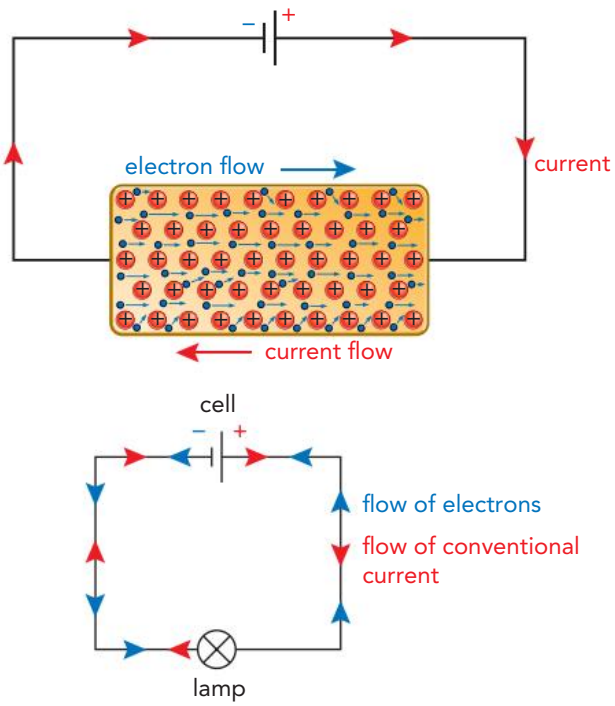

Figure P5.04: Two ways of picturing what happens in an electric circuit: conventional current flows from positive to negative; electrons flow from negative to positive.

KEY WORDS

current: the rate at which electric charge passes a point in a circuit.

direct current (d.c.): electric current that flows in the same direction all the time.

cell: a device that provides an electromotive force (e.m.f.) in a circuit by means of a chemical reaction.

battery: two or more electrical cells connected together in series.

alternating current (a.c.): electric current that (periodically) changes direction.

charge: carried around a circuit by the current; negative charge is carried by electrons.

conventional current: the direction positive charges would flow in a complete circuit, from the positive to negative terminals of a cell, and opposite to the direction that electrons flow.

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Measuring electric current

To measure electric current, we use an **ammeter**. There are two types, as shown in Figure P5.05.

- An analogue meter has a needle, which moves across a scale. Some ammeters have more than one scale (see Figure P5.05). The ammeter shown has two ranges: 0–1 A or 0–5 A. For current below 1 A, a more precise value can be obtained by using the 0–1 A range.
- A digital meter gives a direct read-out in figures.

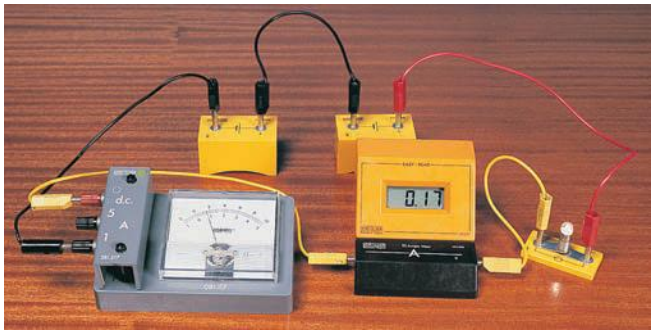

Figure P5.05: Ammeters measure electric current in amps (A). There are two types: analogue (on the left) and digital (on the right). Notice that the analogue meter has two negative (black) connections, labelled 1 and 5. This indicates which scale to read from.

An ammeter is connected into a circuit in series; that is, in the same loop as the other components in the circuit. If the meter is connected the wrong way round, it will give negative readings. To add an ammeter to a circuit, the circuit must be broken (see Figure P5.06).

In a simple series circuit, like the one shown in Figure P5.06, it does not matter where the ammeter is added, since the current is the same all the way round the series circuit. It does not get used up as it flows through the lamp or other components in the circuit.

The reading on an ammeter is in **amperes** (shortened to **amps (A)**, which is the SI unit of currents. Smaller currents may be measured in milliamps (mA) or microamps (μA):

$$1\,\text{mA} = 0.001\,\text{A} = 10^{-3}\,\text{A}$$

$$1\,\mu\text{A} = 0.000\,001\,\text{A} = 10^{-6}\,\text{A}$$

KEY WORDS

ammeter: a meter for measuring electric currents.
ampere, amp (A): the SI unit of electric currents.

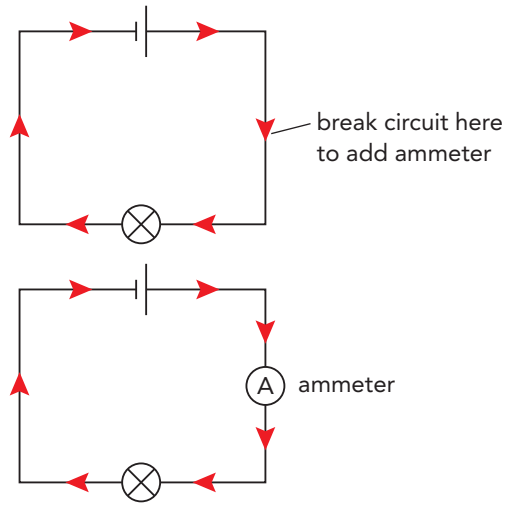

Figure P5.06: Adding an ammeter to a circuit. The ammeter is connected in series so that the current can flow through it.

Questions

P5.03
- **a** What instrument is used to measure electric current?
- **b** How should it be connected in a circuit?
- **c** Draw its circuit symbol.

P5.04 A circuit is set up in which a cell makes an electric current flow through a lamp. Two ammeters are included, one to measure the current flowing into the lamp, the other to measure the current flowing out of the lamp.
- **a** Draw a circuit diagram to represent this circuit.
- **b** What can you say about the readings on the two ammeters?

P5.05
- **a** What is the unit of electric current?
- **b** How many milliamps are there in 1 amp?
- **c** How many microamps are there in 1 amp?

Current and charge

An ammeter measures the rate at which electric charge flows past a point in a circuit. The electric current is defined as the charge (measured in coulombs) passing a point in the circuit per unit of time (usually per second). We can write this relationship between current and charge as an equation, using the quantities and symbols given in Table P5.01:

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KEY EQUATION

$$\text{current(A)} = \frac{\text{charge(C)}}{\text{time(s)}}$$

$$I = \frac{Q}{t}$$

Quantity	Symbol for quantity	Unit	Symbol for unit
current	I	amps	A
charge	Q	coulombs	C
time	t	seconds	s

Table P5.01: Symbols and units for some electrical quantities.

So a current of 10 A passing a point means that 10 C of charge flows past that point every second. You may find it easier to recall this relationship in the following form:

charge (C) = current (A) × time (s)

$$Q = It$$

So, if a current of 10 A flows around a circuit for 5 s, then 50 C of charge flows around the circuit.

Worked example P5.01 shows how to calculate the charge that flows in a circuit.

WORKED EXAMPLE P5.01

A current of 150 mA flows around a circuit for one minute. How much electric charge flows around the circuit in this time?

Step 1: Write down what you know, and what you want to know. Put all quantities in the units shown in Table P5.01.

$I = 150\,\text{mA} = 0.15\,\text{A}$ (or $150 \times 10^{-3}\,\text{A}$)

$t = 1$ minute $= 60\,\text{s}$

$Q = ?$

Step 2: Write down an appropriate form of the equation relating Q, I and t. Substitute values and calculate the answer.

$Q = I\,t$

$Q = 0.15\,\text{A} \times 60\,\text{s} = 9\,\text{C}$

Answer

9 coulombs of charge flow around the circuit.

Questions

P5.06 Which of the following equations shows the correct relationship between electrical units?

$1\,\text{A} = 1\frac{\text{C}}{\text{s}}$

$1\,\text{C} = 1\frac{\text{A}}{\text{s}}$

P5.07 Calculate the missing values **a–d** in Table P5.02. Show all your working.

Charge	Current	Time
220 C	2 A	**a**
57.6 C	**b**	3 hours
c	0.5 A	9 minutes
5.4 C	70 mA	**d**

Table P5.02: Calculations using $Q = I\,t$.

Transferring energy

We use electric circuits to transfer energy. The energy is supplied by a cell or battery, or by plugging into the mains.

Figure P5.07a shows a cell. This is a store of chemical energy. Two or more cells together is called a battery (Figure P5.07b). Cells and batteries transfer chemical energy into electrical energy.

Electricity for the mains is supplied by generators. A generator is turned, usually by steam, water or wind (Figure P5.07c), transferring kinetic energy into electrical energy.

The store of electrical energy supplied by the mains can be transferred to useful stores when current flows. For example, the fan (Figure P5.07d), uses an electric motor to transfer electrical energy into kinetic energy to turn the fan.

Voltage in electric circuits

Figure P5.08 shows a circuit in which a cell causes current to flow through a lamp. The cell provides the **voltage** needed to make the current flow through the lamp.

KEY WORD

voltage: the voltage of a source causes current to flow in a circuit.

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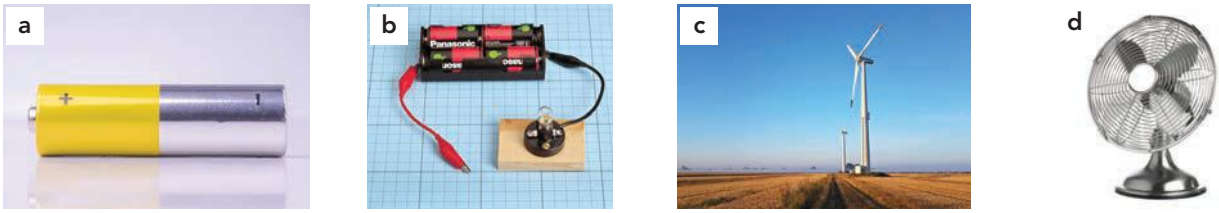

Figure P5.07 a: A cell is a store of electrical energy. **b:** A battery is a number of cells connected together. **c:** A wind turbine turns a generator. **d:** The motor in this fan turns the blades and transfers electrical energy to kinetic energy.

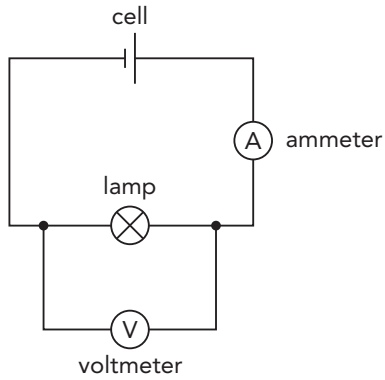

Figure P5.08: The cell provides the potential difference (p.d.) needed to push the current around the circuit. The ammeter measures the current flowing through the lamp. The voltmeter measures the p.d. across it. The ammeter is connected in series in the circuit. The voltmeter is connected in parallel in the circuit.

Voltage is measured using a **voltmeter** which, like an ammeter, can be either analogue or digital. Voltmeters are always connected in **parallel** with a component. This means it is connected across a component in a separate loop. The reading on a voltmeter is in **volts (V)**, but they have different ranges. Smaller voltages may be measured in millivolts (mV) or microvolts (μV).

In a circuit with several components in series, the voltage from the source is shared between the components. Figure P5.09 shows a 12 V battery (made up of two 6 V cells) causing current to flow in a lamp and a motor.

KEY WORDS

voltmeter: a meter for measuring the p.d. (voltage) between two points.

parallel: in a parallel circuit, components are connected in separate loops.

volt (V): the SI unit of voltage (p.d. or e.m.f.).

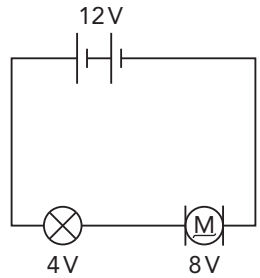

Figure P5.09: The voltage of a source is shared between the components in a series circuit.

A voltmeter across the lamp would read 4 V and a voltmeter across the motor would read 8 V. The 12 V is shared between the components.

Electromotive force and potential difference

There is a special name for the voltage across a cell. It is called the **electromotive force (e.m.f.)** of the cell and it is also measured in volts. The term can be misleading, since e.m.f. is a voltage, not a force. Any component that causes a current to flow around a circuit is said to be a source of e.m.f. Examples are cells, batteries and power supplies.

A cell is a store of chemical energy. When the cell is connected in a circuit, this energy is transferred by the movement of charge around the circuit. Work is done in moving the electrons around the circuit. E.m.f. can be defined as the amount of electrical work done in moving one unit (one coulomb) of charge around a complete circuit.

KEY WORDS

electromotive force (e.m.f.): the voltage across the terminals of a source or the electrical work done by a source (cell, battery, for example) in moving charge around a circuit.

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Potential difference (p.d.) is the name given to the voltage across a component in a circuit. The p.d. between two points in a circuit is the work which a unit of charge (a coulomb) has to do to move between the two points. Potential difference is also measured in volts.

Consider the circuit in Figure P5.09. The e.m.f of the battery is 12 V. The p.d. across the lamp is 4 V and the p.d. across the motor is 8 V. More work is done moving charge through the motor than the lamp, suggesting it is more difficult for current to flow through the motor than through the lamp.

KEY WORDS

potential difference (p.d.): the work done by (a unit) charge passing through an electrical component; another name for the voltage between two points.

Questions

P5.08 **a** Name the device used to measure voltage.

b Copy the circuit diagram from Figure P5.09 and add a voltmeter to measure the voltage across the lamp.

P5.09 **a** What do the letters p.d. stand for?

b What name is given to the p.d. across a cell or battery?

c What unit is p.d. measured in?

What is resistance?

Electrical **resistance** is a measure of how hard it is for current to flow in a circuit. Components such as lamps and motors resist the flow of current. The greater the resistance, the bigger the voltage needed to make the same current flow. Resistance can be thought of as the number of volts needed to make one amp of current flow through a component.

The electrical resistance of a component is measured in **ohms (Ω)**. It is defined as the potential difference across the component divided by the current passing through it:

KEY EQUATION

$$\text{resistance} = \frac{\text{p.d.}}{\text{current}}$$

$$R = \frac{V}{I}$$

KEY WORDS

resistance: a measure of how difficult it is for an electric current to flow through a device or a component in a circuit; it is the p.d. across a component divided by the current through it.

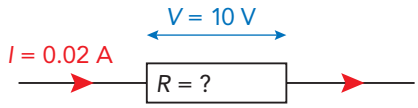
ohm (Ω): the SI unit of electrical resistance.

Worked example P5.02 shows how to calculate the resistance of a resistor.

WORKED EXAMPLE P5.02

A resistor allows a current of 0.02 A to flow through it when there is a p.d. of 10.0 V between its ends. What is its resistance?

Step 1: Write down what you know and what you want to know. You may prefer to write these quantities on a sketch of the situation like this:



current $I = 0.02\,\text{A}$

p.d. $V = 10.0\,\text{V}$

resistance $R = ?$

Step 2: Write down the equation for R. Substitute values and calculate the answer.

$$R = \frac{V}{I}$$

$$= \frac{10.0\,\text{V}}{0.02\,\text{A}}$$

$$= 500\,\Omega$$

Answer

So, the resistance of the resistor is 500 Ω.

Measuring resistance

In order to determine resistance, we need to know the current flowing through the resistor (measured by the ammeter) and the p.d. across it (measured by the voltmeter). This can be done using the circuit shown in Figure P5.10. The resistance can be calculated by dividing voltage by current.

Remember:

- Ammeters are connected in series so that the current can flow through them.
- Voltmeters are connected in parallel to measure the p.d. across the component.

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EXPERIMENTAL SKILLS P5.01

Measuring the resistance of a resistor

In this experiment you will measure current and voltage. You will use these to calculate the resistance of a wire.

You will need:

- power supply
- 5 insulated wires
- resistor
- ammeter
- voltmeter.

Safety

The resistor may become hot when current flows. Only switch on the power supply when you are ready to take ammeter and voltmeter readings. Switch it off as soon as you have taken your readings.

Getting started

State what devices you will use to measure voltage and current and describe how they should be wired into the circuit.

Method

1 Set up the circuit as shown in Figure P5.10. Set the power supply to 2V.

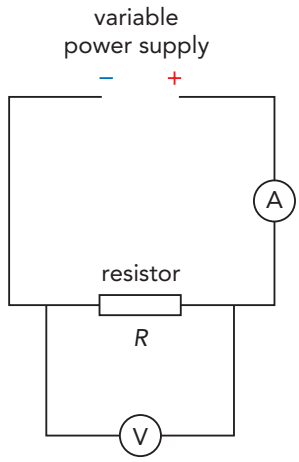

Figure P5.10: A circuit for investigating how the current through a resistor changes as the voltage across it varies. The power supply can be adjusted to give a range of values of voltage (typically from 0V to 12V).

CONTINUED: P5.01

2 Draw a table like P5.03.

Voltage / V	Current / A	Resistance / Ω

Table P5.03: Voltage and current can be measured and used to calculate resistance.

3 Turn on the power supply and record the ammeter and voltmeter readings in the table. Note that, for accuracy, the voltage should be read from the voltmeter, not the power supply setting.

4 Repeat step three for power supply settings 4V, 6V, 8V, 10V and 12V.

5 Calculate the resistance values using $R = \frac{V}{I}$ and record the results in the table.

Question

Does the resistance of a resistor change when the voltage across it changes?

Current–voltage graphs

A graph of current against potential difference for a component tells us about the resistance of the component.

- The p.d. V is on the x-axis, because this is the quantity we vary. It is the independent variable.
- The current I is on the y-axis, because this is the quantity that varies as we change V. It is the dependent variable.

Figure P5.11 shows the results of an experiment similar to Experimental skills P5.01.

In this case, the graph is a straight line that passes through the origin. This is what we expect because the equation $I = \frac{V}{R}$ shows that the current I is proportional to the p.d., V. The resistance of the resistor is constant. It is easy to predict the current that will flow through this resistor because the current is directly proportional to the p.d. across it. Double the voltage gives double the current, and so on.

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a

p.d. V/V	Current I/A	Resistance R/Ω
2.0	0.08	25.0
4.0	0.17	23.5
6.0	0.24	25.0
8.0	0.31	25.8
10.0	0.40	25.0
12.0	0.49	24.5

b

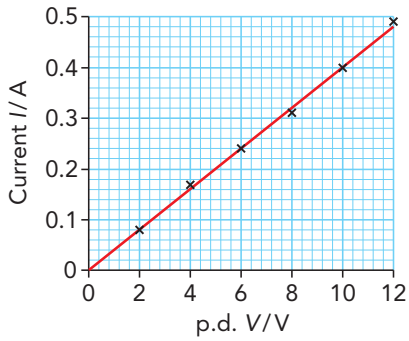

Figure P5.11 a: Results table for an experiment to determine resistance. **b:** The current–voltage graph for the data.

Figure P5.12 shows what happens if we use a filament lamp instead of a resistor. You can see that the current–voltage graph for the filament lamp is curved.

- At first, for low voltages, the graph is straight, showing that the current increases at a steady rate as the voltage is increased.
- At higher voltages, the graph starts to curve over. The current increases more and more slowly as the voltage is increased. This shows that the resistance increases.

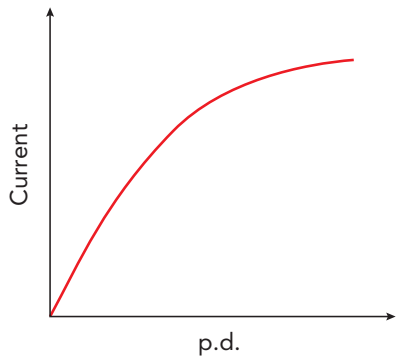

Figure P5.12: The current–voltage graph for a filament lamp. The graph is not a straight line through the origin, showing that the lamp does not have constant resistance.

Why does the resistance increase? As the current increases, kinetic energy of the electrons passing through the filament is transferred to the internal energy of the filament, causing it to heat up, so that its atoms vibrate more. This means that there will be more collisions between electrons and the vibrating atoms. This makes it more difficult for the electrons to flow. The resistance is increased.

In a similar way, it is more difficult to move through a crowd where people are moving in random directions compared to a crowd of people who are standing still.

Figure P5.13 shows the typical shapes of the current–voltage graphs for constant resistors, for a filament lamp and for a diode. In Figure P5.13a, resistor Q has a higher resistance than resistor P. We can tell this because the current flowing through Q is always less than the current through P, for any voltage.

Notice that these graphs show both positive and negative voltages. A negative current means one flowing in the opposite direction. This is achieved by connecting the cell or power supply the other way round. Figures P5.13a and b are symmetrical, showing that, whichever way round the components are connected, the current will be the same for a given voltage.

Figure P5.13c is the *I*–*V* graph for a diode, which is not symmetrical. A diode only allows current to flow in one direction. The arrow on the diode symbol indicates the direction that conventional current can flow.

Questions

P5.10 **a** What is the resistance of a lamp if a current of 5.0 A flows through it when it is connected to a 240 V supply?

b When the voltage across the lamp is increased, will the current flowing increase or decrease?

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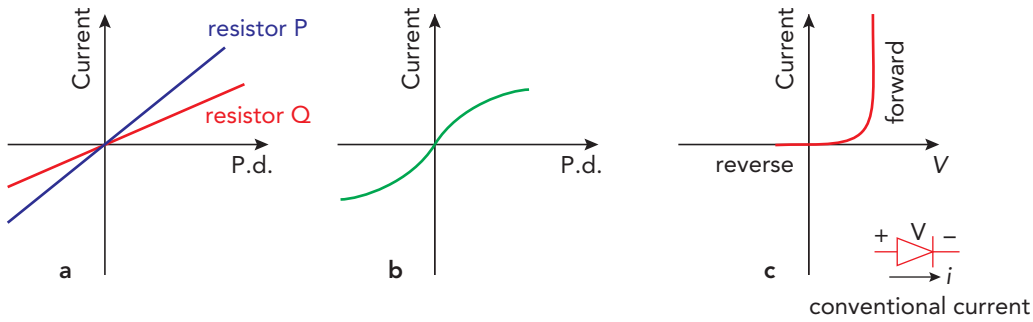

Figure P5.13: Typical current–voltage graphs. **a:** For two resistors. **b:** For a filament lamp. **c:** For a diode.

P5.11 Calculate the missing values **a–d** in Table P5.04. Show all your working.

Voltage / V	Current / A	Resistance / Ω
240	2	**a**
12	**b**	3000
c	0.5	15
120	80	**d**

Table P5.04: Calculations using V = IR.

P5.12 **a** What voltage is needed to make a current of 2.0 A flow through a 30 Ω resistor?

b What voltage is required when the resistance is doubled?

P5.13 **a** A voltage of 240 V across a resistor causes a current of 80 mA to flow through it. What is the resistance of the resistor?

b What voltage would cause a current of 40 mA to flow through the resistor?

P5.14 What current flows when a voltage of 7.5 V is connected across a 2 kΩ resistor?

SELF ASSESSMENT

Look back at your working for questions P5.10–P5.14. Are you using the following steps?

- Identify what you know and what you need to find out.
- Write down the equation.
- Rearrange the equation if necessary.
- Substitute the values into the equation.
- Calculate the answer.
- Give the units.

Write out *one* question and answer as if it was to be a Worked example in this book.

The resistance of metallic conductors

Many resistors are made of coils of resistance wire. The resistance of different wires can be found using the method in Experimental skills P5.01.

Figure P5.14 shows the results of an experiment investigating how the length of a wire affects its resistance.

The graph is a straight line passing through the origin, showing that the resistance of a wire is directly proportional to its length.

Similar investigations show how the resistance of a wire depends on its thickness. Figure P5.15 shows the resistances of equal lengths of wire which have different cross-sectional areas.

The graph in Figure P5.15 shows that the resistance of a wire is inversely proportional to its cross-sectional area.

We have seen that the resistance of a wire depends on its length and its thickness. This is true for any metallic conductor:

- Resistance is directly proportional to length.
- Resistance is inversely proportional to the cross-sectional area.

Suppose that we have a 4.0-metre length of wire. Its resistance is 100 Ω. What will be the resistance of a 2.0-metre length of wire with twice the cross-sectional area? Notice that making the wire shorter will reduce its resistance and increasing its area will also reduce its resistance.

- Halving the length gives half the resistance = 50 Ω.
- Doubling the area halves the resistance again = 25 Ω.

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a

Length of wire / cm	Voltage / V	Current / A	Resistance / Ω
20	1.2	0.90	1.3
40	1.7	0.63	2.7
60	1.8	0.41	4.4
80	2.0	0.34	5.9
100	2.4	0.30	8.0

b

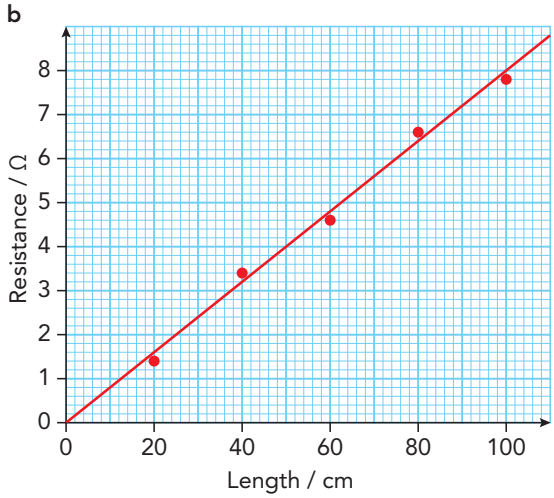

Figure P5.14 a: Typical results for investigation of the effect of length on the resistance of a wire. **b:** Graph of *resistance* against *length*.

a

Cross-sectional area of wire / mm^2	Resistance of wire / Ω
0.25	2.1
0.5	3.9
0.75	6.0
1.0	8.2
1.25	9.9

b

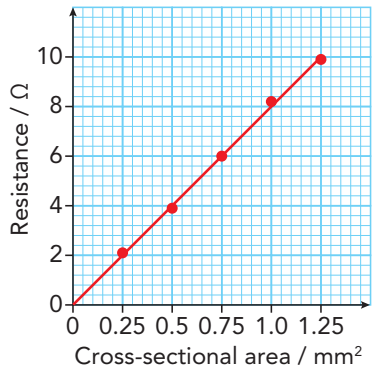

Figure P5.15 a: Typical results for investigation of the effect of cross-sectional area on the resistance of a wire. **b:** Graph of *resistance* against *length*.

Questions

P5.15 A student cuts two pieces of wire, one long and one short, from a reel.

- **a** Which piece of wire will have the greater resistance?
- **b** Draw a circuit diagram to show how you would check your answer by measuring the resistances of the two pieces of wire.

P5.16 A 2.0-metre length of wire has a resistance of 4.0 Ω.

- **a** What is the resistance of a piece of the same wire of length 20.0 metres?
- **b** What is the resistance of a 4.0-metre wire with half the cross-sectional area, made of the same material?

ACTIVITY P5.01

What have I learnt?

Take two minutes to summarise what you have learnt so far in this chapter on one sheet of paper.

Now, take two more minutes to condense your notes. You may use six words and two diagrams.

Compare summaries with a partner. Assume that you can use only three words and one diagram as a reminder in a test. Which diagram and three words would you choose?

Reflection

Which part of Activity P5.01 did you find most useful? Summarising, condensing or sharing? Consider how this might help you when revising for a test.

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P5.03 Electrical energy and electrical power

Electrical energy

We use electricity because it is a good way of transferring energy from place to place. If you switch on an electric heater, you are getting the benefit of the energy released as fuel is burnt in a power station, which may be over 100 km away, or transferred from energy from renewable sources such as the Sun or wind. Appliances such as lamps, heaters and motors transfer the electrical energy to useful energy stores – light in the case of the lamps, heat for the heater and kinetic for the motor. All this energy is eventually transferred to the surroundings.

Electrical power

Most electrical appliances have a label that shows their **electrical power** rating. An example is shown in Figure P5.16.

Figure P5.16: A label from an electric kettle.

Power ratings are indicated in watts (W) or kilowatts (kW). The power rating of an appliance shows the rate at which it transfers energy. The kettle shown in Figure P5.16 has a power ranging between 2600 W and 3000 W, meaning it transfers 2600–3000 J of energy each second.

KEY WORDS

electrical power: the rate at which electrical energy is transferred.

Voltage and power

The voltage of a supply tells us how much energy it transfers to charges flowing around the circuit. The greater the current flowing around the circuit, the faster that energy is transferred. So, the rate at which energy is transferred in the circuit (the power, P) depends on both the voltage, V, of the supply and the current, I, that it pushes round the circuit.

The following equation shows how to calculate the electrical power:

KEY EQUATION

$$\text{power} = \text{current} \times \text{p.d.}$$

$$P = IV$$

Calculating energy

Electrical power is the rate at which energy is transferred. We can use the equation we saw in Chapter P2:

$$\text{energy transferred (J)} = \text{power (W)} \times \text{time (s)}$$

We can combine this with the equation $P = IV$ to give an equation for electrical energy transferred, E, in terms of current and voltage:

KEY EQUATION

$$\text{energy transferred} = \text{current} \times \text{p.d.} \times \text{time}$$

$$E = IVt$$

Worked example P5.03 shows how to calculate the power of a device and how much energy is transferred in a given time.

WORKED EXAMPLE P5.03

An electric fan runs from the 230 V mains supply. The current flowing through it is 0.40 A. At what rate is electrical energy transferred by the fan? How much energy is transferred in one minute?

Step 1: First, we have to calculate the rate at which electrical energy is transferred. This is the power, P. Write down what you know and what you want to know.

$V = 230\,\text{V}$ $I = 0.40\,\text{A}$ $P = ?$

Step 2: Write down the equation for power, which involves V and I, substitute values and solve.

$P = IV$

$P = 0.40\,\text{A} \times 230\,\text{V} = 92\,\text{W}$

Step 3: To calculate the energy transferred in 1 minute, use $E = Pt$ (or $E = IVt$). Recall that time, t, must be in seconds.

$E = 92\,\text{W} \times 60\,\text{s} = 5520\,\text{J}$

Answer

So, the fan's power is 92 W and it transfers 5520 J of energy each minute.

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Questions

P5.17 Write down an equation linking watts, volts and amps.

P5.18 Calculate the missing values **a–d** in Table P5.05. Show all your working.

Voltage / V	Current / A	Power / P
240	2	**a**
12	**b**	60
c	0.5	15
120	80	**d**

Table P5.05: Calculations using $P = IV$.

P5.19 A 12 V power supply pushes a current of 6.0 A through a resistor. At what rate is energy transferred to the resistor?

P5.20 A tropical fish tank is fitted with an electric heater, which has a power rating of 50 W.

The heater is connected to a 240 V supply. What current flows through the heater when it is switched on?

P5.21 How much energy is transformed by an electric lamp in an hour if a current of 20 mA flows through it when it is connected to a 120 V supply?

Units of electrical energy

Up to now we have used the SI unit for energy – the joule. However a joule is a tiny amount of energy and is not a suitable unit for measuring the electrical energy used in a house.

For example, a 2000 W electric heater is used for 2 hours. The energy used is:

$$E = P \times t = 2000 \times 2 \times 60 \times 60 = 14\,400\,000\,\text{J}.$$

Clearly the number of joules used in a typical home will be huge, so we use an alternative unit called the kilowatt-hour. A kilowatt-hour is the energy used when a 1 kW device is used for 1 hour.

The equation for working out the number of kWh of electrical energy that is being used is:

KEY EQUATION

energy transferred (kWh) = power (kW) × time (h)

The energy used by the heater in kWh is:

$$E = P \times t = 2 \times 2 = 4\,\text{kWh}$$

(a much more manageable number!)

Kilowatt-hours are measured using a domestic electricity meter, like the ones shown in Figure P5.17. Electricity bills charge for the number of kWh used.

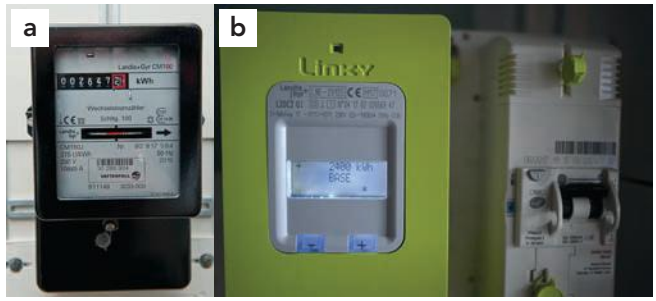

Figure P5.17 a: An electricity meter. **b:** A typical smart electricity meter, which can be accessed remotely so that there is no need for someone to come to your house to read your meter.

Worked example P5.04 shows how the number of units a device uses depends on how much power it transfers and the length of time it operates.

WORKED EXAMPLE P5.04

Marcus switches on a water heater for two hours. The power of the heater is 3.5 kW. How much energy is transferred in kWh (units)?

Step 1: Start by writing down what you know and what you want to know.

power = 3.5 kW

time = 2 hours

energy transferred (kWh) = ?

Step 2: Now write down the equation for energy transferred in kWh.

energy transferred (kWh) = power (kW) × time (hours)

Step 3: Substitute the values of the quantities on the right-hand side and calculate the answer.

energy transferred (kWh) = 3.5 kW × 2 hours = 7 kWh

Answer

The water heater uses 7 kWh (or 7 units).

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Questions

P5.22 Calculate the number of kWh of energy transferred by:

- **a** a 2.5 kW iron used for 2 hours.
- **b** a 3 kW electric iron used for 30 minutes
- **c** a 100 W lamp used for 5 hours.

P5.23 A 3 kW air conditioning unit used 216 kWh of electricity. Calculate how many days it was switched on for.

P5.24 Eshan recorded the readings on his family's electricity meter at the beginning and end of one month. The readings were 990 987 and 991 013. Electricity costs 0.5 dirhams per unit. Calculate the cost of the electrical energy used by Eshan's family in this month.

P5.25 Use the information in Table P5.06 to work out the missing values **a**–**j**. Assume that electricity costs 16p per unit.

Appliance	Power	Time	kWh / unit	Cost
desktop computer	**a**	3 hours	1.3	**b**
microwave oven	870 W	**c**	0.87	**d**
television	**e**	12 hours	1.0	**f**
energy efficient lamp	9 W	**g**	4.5×10^{-2}	**h**
kettle	2 kW	3 minutes	**i**	**j**

Table P5.06: Calculating the cost of running electrical appliances.

P5.04 Magnetism

Permanent magnets

A compass needle is like a **bar magnet**. When it is free to rotate (Figure P5.18), it turns to point north–south. One end points north – this is the magnet's **north pole**, pointing roughly in the direction of the Earth's geographical North Pole. The other end is the magnet's **south pole**. Sometimes, the north and south poles of a magnet are called the north-seeking pole and south-seeking pole, respectively.

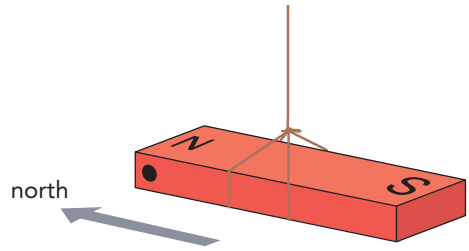

Figure P5.18: A freely suspended magnet turns so that it points north–south.

KEY WORDS

bar magnet: a rectangular-shaped permanent magnet with a north pole at one end and a south pole at the other.

north pole (N pole): the end of a magnet which is attracted to the Earth's North Pole.

south pole (S pole): the end of a magnet which is attracted to the Earth's South Pole.

When two magnets are brought close together, there is a force between them. The north pole of one will attract the south pole of the other. Two north poles will repel each other, and two south poles will repel each other (Figure P5.19). This is summarised as:

- like poles repel
- unlike poles attract.

'Like poles' means poles that are the same – both north, or both south. 'Unlike poles' means opposite poles – one north and the other south.

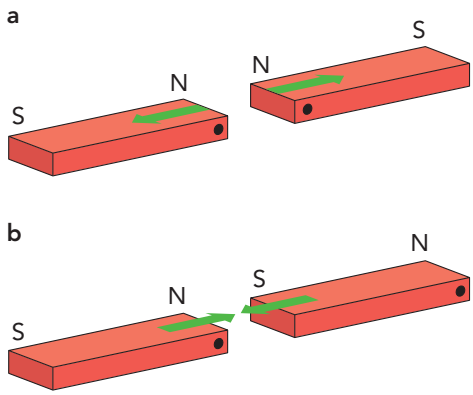

Figure P5.19 a: Two like magnetic poles repel one another. **b:** Two unlike magnetic poles attract each other.

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Since the north pole of the compass needle is attracted to the Earth's North Pole, it follows that there must be a magnetic south pole up there, under the Arctic ice. The Earth itself is **magnetised**, rather as if there was a giant bar magnet inside it.

Magnetic materials

Magnetic materials are attracted by a magnet and can be magnetised. The most common magnetic materials contain iron. Cobalt and nickel are also magnetic.

Most metals and almost all non-metals are not magnetic.

Though they can be magnetised, not all pieces of magnetic material are magnets. They first need to be magnetised. This can be done by stroking the material with another magnet or using a coil carrying electric current. A piece of a magnetic material which has not been magnetised is said to be **unmagnetised**.

Permanent and temporary magnets

A compass needle is a **permanent magnet**. Like many bar magnets, it is made of hard steel.

Magnetic materials may be classified as **hard** (permanent) or **soft** (temporary). Table P5.07 summarises the difference. A soft magnetic material such as soft iron can be magnetised and demagnetised easily.

KEY WORDS

magnetised: when a magnetic material has been made into a magnet.

unmagnetised: when a magnetic material has not been made into a magnet.

permanent magnet: magnetised magnetic material that produces its own magnetic field that does not get weaker with time.

hard (material): a material that, once magnetised, is difficult to demagnetise.

soft (material): a material that, once magnetised, is easy to demagnetise.

Type of magnetic material	Description	Examples	Uses
hard	retains magnetism well, but difficult to magnetise in the first place	hard steel	permanent magnets, compass needles, loudspeaker magnets
soft	easy to magnetise, but readily loses its magnetism	soft iron	cores for electromagnets, transformers and radio aerials

Table P5.07: Hard and soft magnetic materials. Hard steel is both hard to bend and difficult to magnetise and demagnetise. Soft iron is both easier to bend and easier to magnetise and demagnetise.

Induced magnetism

A bar magnet is an example of a permanent magnet. It can remain magnetised. Its magnetism does not disappear. Permanent magnets are made of hard magnetic materials.

A permanent magnet can attract or repel another permanent magnet. It can also attract other unmagnetised magnetic materials. For example, a bar magnet can attract steel pins or paper clips, and a fridge magnet can stick to the steel door of the fridge.

What is going on here? Steel pins are made of a magnetic material. When the north pole of a permanent magnet is brought close to a pin, the pin is attracted (see Figure P5.20). The attraction tells us that the end of the pin nearest the magnetic pole must be a magnetic south pole, as shown in Figure P5.20. This is known as **induced magnetism**. The two objects will have opposite polarities. In this example, the pin will have a south pole induced in the end nearest the north pole of a bar magnet. When the permanent magnet is removed, the pin will return to its unmagnetised state (or it may retain a small amount of magnetism).

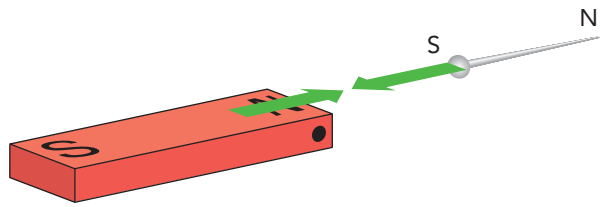

Figure P5.20: A steel pin is temporarily magnetised when a permanent magnet is brought close to it.

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KEY WORDS

induced magnetism: when a magnetic material is only magnetised when placed in a magnetic field (for example, when brought close to the pole of a permanent magnet).

Questions

P5.26 Name *three* magnetic elements.

P5.27 What is the rule about whether magnetic poles repel or attract?

P5.28 Copy and complete Table P5.08.

Type of magnetic material	Description	Examples	Uses
hard			
soft			

Table P5.08: The magnetic properties of different metals make them useful for different applications.

P5.29 Why is it better to make a permanent magnet from steel rather than iron?

Magnetic fields

A magnet affects any piece of magnetic material that is nearby. We say that there is a **magnetic field** around the magnet. Experiments with iron filings or small **plotting compasses** can illustrate the magnetic field of a magnet. Figure P5.21 shows the field of a bar magnet as revealed by iron filings.

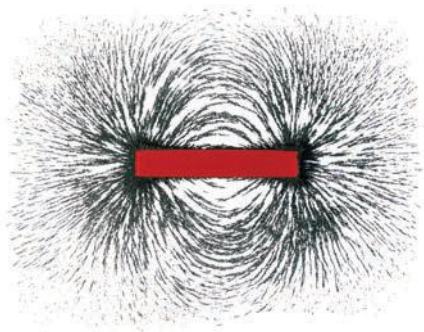

Figure P5.21: The magnetic field pattern of a bar magnet is illustrated by iron filings. The iron filings cluster most strongly around the two poles of the magnet. This is where the field is strongest.

Figure P5.22 shows how we represent the magnetic field of a single bar magnet using **magnetic field lines**. The field fills all the space around the magnet, but we only draw a few lines to represent it. The pattern tells us two things about the field:

- Direction: the direction of a magnetic field line at any point is the direction of the force on the north pole of a magnet at that point. Field lines come out of north poles and go in to south poles.
- Strength: lines that are close together indicate a strong field.

KEY WORDS

magnetic field: a region of space around a magnet in which a magnetic pole experiences (feels) a force.

plotting compass: very small compass with a needle that lines up with magnetic field lines, allowing changes in field direction to be observed and plotted over a very short distance.

magnetic field lines: represent the direction the magnetic force would have on the north pole of a magnet.

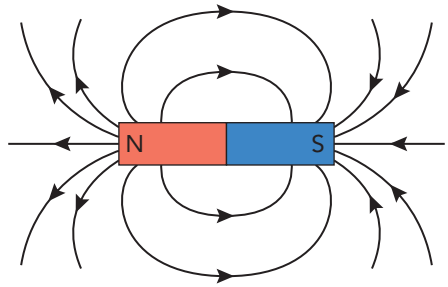

Figure P5.22: Field lines are used to represent the magnetic field around a bar magnet.

Question

P5.30

a Sketch the field pattern around a bar magnet.

b Someone has drawn the field pattern but forgotten to label the poles. Do the arrows point towards or away from the magnetic north pole?

c When looking at a field pattern, how would you know where the magnetic field is strongest?

d Where is the field strongest on a bar magnet?

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Electromagnets

An **electromagnet** is made by the flow of electric current. A typical electromagnet is made from a coil of copper wire (sometimes called a **solenoid**). When a current flows through the wire, there is a magnetic field around the coil. The coil does not have to be made from a magnetic material. It is the electric current that produces the magnetic field.

KEY WORDS

electromagnet: a coil of wire that acts as a magnet when an electric current passes through it.

solenoid: an electromagnet made by passing a current through a coil of wire.

You can see that the magnetic field around a solenoid (Figure P5.23) is similar to that around a bar magnet (Figure P5.22). One end of the coil is a north pole and the other end is a south pole. In Figure P5.23, the field lines emerge from the left-hand end, so this is the north pole.

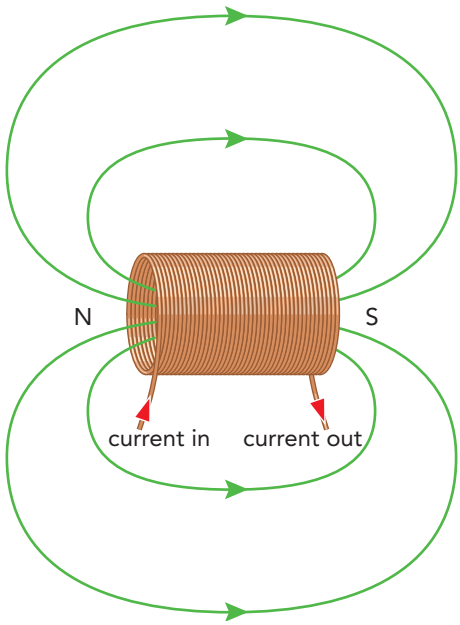

Figure P5.23: A solenoid. When a current flows through the wire, a magnetic field is produced. The field is similar in shape to that of a bar magnet.

Electromagnets have the advantage that they can be turned on and off by switching off the current. This is very useful. For example, electromagnetic cranes move large pieces of metal around in a scrapyard (Figure P5.24). The current is switched on to start the magnet and pick up the scrap metal. When it has been moved to the correct position, the electromagnet is switched off and the metal is released.

Electromagnets are also used in electric doorbells, loudspeakers, electric motors and transformers.

Figure P5.24: Using an electromagnet in a scrapyard.

Question

P5.31 **a** What are the advantages of an electromagnet over a permanent magnet?

b What does an electromagnet need that a permanent magnet does not?

P5.05 More about electrical charge

We experience **static electricity** in a number of ways in everyday life, including lightning flashes. You may have noticed tiny sparks when you take off clothes made of synthetic fibres. You may have felt a small shock when getting out of a car. An **electrostatic charge** builds up on the car and then discharges through you when you touch the metal door. You may have rubbed a balloon on your clothes or hair and seen how it will stick to a wall or ceiling.

KEY WORDS

static electricity: electric charge held by a charged insulator.

electrostatic charge: a property of an object that causes it to attract or repel other objects with charge.

When you rub a plastic object (for example, a balloon) with a cloth, both are likely to become electrically charged (Figure P5.25). You can tell that this is so by holding the balloon or the cloth close to your hair as they attract the hair.

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Figure P5.25: Objects which have electrostatic charge can attract light objects such as hair or paper.

Questions

P5.32 Explain why, after walking on a nylon carpet, you may get a small shock when you touch a metal door handle.

P5.33 List *three* insulators and *three* conductors.

Friction and charging

As far back as the Ancient Greeks, people have observed static charging. It is only since the discovery of the electron in 1897 that we have been able to explain how charging happens.

Figure P5.26: An insect trapped in resin which has hardened to become amber. The Ancient Greeks observed that amber became charged when it was rubbed.

It is the force of friction that causes charging. When a plastic rod is rubbed on a cloth, friction transfers tiny particles, called electrons, from one material to the other. When the rod is made of polythene, electrons are usually transferred from the cloth to the rod.

Electrons are a part of every atom. They are negatively charged and they are found on the outside of the atom. The nucleus in the centre of the atom has a positive charge. The positive and negative charges in an atom are equal, so, overall, an atom has no electric charge. We say that it is **neutral**. Since the outer electrons are relatively weakly held in the atom, they can be pulled away by the force of friction. When an atom has lost an electron, it becomes positively charged.

Charging is always the result of gaining or losing electrons. Positive charge is not transferred.

- An object which gains electrons becomes negative.
- An object which loses electrons becomes positive.

Since a polythene rod becomes negatively charged when it is rubbed with a cloth, we can imagine electrons being transferred from the cloth to the rod (see Figure P5.27).

Remember that it takes two different materials to generate static electricity. One material becomes positive, the other negative.

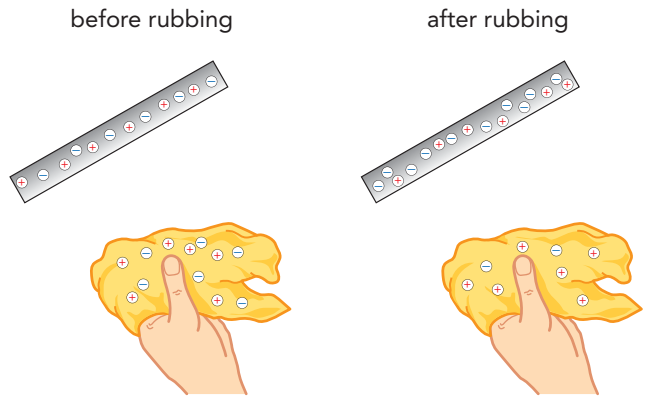

Figure P5.27: When a polythene rod is rubbed with a cloth, electrons are transferred from the cloth to the polythene. The rod now has an overall negative charge and the cloth has an overall positive charge.

Conductors and insulators

You may have noticed that all the examples of objects becoming charged involve non-metals. Metals are **electrical conductors**, which means electrons can move through them and the metal does not stay charged. Gold and copper are particularly good electrical conductors. Non-metals, such as glass, plastic (polymers) and amber, are **electrical insulators**.

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KEY WORDS

neutral: having no overall positive or negative charge.

electrical conductor: a substance that allows the flow of electrons (electric current).

electrical insulator: a substance that inhibits the flow of electrons (electric current).

In insulators, the electrons are tightly bound to their atoms and not easily removed. In conductors, some of the electrons are free to move between atoms.

A charged insulator will keep its charge because charges cannot move through it.

If a charge is given to a conductor, the charge will flow through it and into the earth.

Electric fields

A charged object can affect other objects, both charged and uncharged, without actually touching them. For example, a charged plastic rod can exert a force on another charged rod placed close by.

We say that there is an **electric field** around a charged object. Any charged object placed in the field will experience a force on it.

Figure P5.28: The comb has been charged by rubbing it. It attracts the water when it is held close to it.

KEY WORDS

electric field: a region of space in which an electric charge will experience a force.

An electric field can be represented by electric field lines. These show the direction of the force on a positive charge placed at that point in the field. Figure P5.29 shows the field around a negatively charged sphere. Notice that the field lines point towards the sphere, because positive charge will be attracted to the negatively charged sphere.

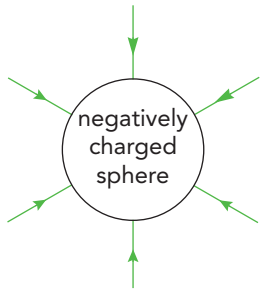

Figure P5.29: The electric field around a negatively charged object.

There are similarities between electric fields and magnetic fields, but take care not to confuse electric fields with magnetic fields. A magnet does not attract electric charges. A charged object does not attract a magnet.

Question

P5.34 **a** Copy and complete these sentences.

When a polythene rod is rubbed with a cloth, _____ move from the _____ to the _____.

This means the rod becomes _____ and the cloth becomes _____.

b Draw a diagram similar to Figure P5.27 to show how an acetate rod becomes positively charged by losing electrons.

c Write sentences similar to those you completed in Question P5.34a to explain how the acetate becomes charged.

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PROJECT P5.01 SHINING THE LIGHT ON WHAT LAMP TO USE

Design a public awareness and education campaign to persuade people to switch to using LED lamps.

Your campaign must include an eye-catching and scientifically accurate poster or leaflet that can be understood by the public. One way to encourage people to read your leaflet is to provide a guide for choosing the correct bulb, including whether they need a screw or bayonet fitting.

You must include a table that compares the cost of the different light bulbs. This cost should include the purchase price plus the running cost over 20 years.

If you are working in pairs or small teams, you could also produce a podcast.

Background

Many people are already aware that energy-saving light bulbs can reduce carbon emissions and save them money. However, energy-saving light bulbs are often more expensive to buy, and some people think they prefer the colour of light emitted by tungsten lamps or prefer the look of the filament that can be seen through the glass when the lamp is off (Figure P5.30). Your campaign should emphasise that the colour output of energy-saving bulbs can match that of the traditional tungsten filament bulb.

Figure P5.30: Different light bulbs. From left to right: LED, tungsten filament light, CFL.

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CONTINUED

Energy-saving light bulbs come in two varieties: compact fluorescent lamps (CFL) and clusters of light emitting diodes (LED). Older people remember LEDs when they produced quite a harsh light that was highly directional (sending out a beam of light in one direction). This was not suitable for lighting a room. LED lights have improved and some have even been made to look exactly like filament light bulbs. However, energy-saving light bulbs, particularly CFLs, contain electronic circuitry that is difficult to recycle. CFLs also contain mercury, which is toxic and a danger to health.

People need to be educated to look for bulbs that give out the brightness they want (measured in lumens) instead of the power consumed (measured in watts). For example, a 60 W tungsten filament light bulb, a 14 W CFL and a 10 W LED all emit 850 lumens.

As part of the education campaign, you will need to compare the cost of using the different light bulbs all producing the same light output (say 850 lumens) and switched on for 25 000 hours over a period of 20 years. In the table, we have assumed that the light bulbs all emit 850 lumens. When you research light bulbs, note that tungsten filament light bulbs are sometimes called incandescent light bulbs or halogen light bulbs. Only use the data in Table P5.09 if you really do not have time to research up-to-date numbers. By the time you read this book, CFLs and LEDs may have become even more efficient, they may last longer and the cost of electricity will certainly have changed.

	Type of bulb		
Quantity	Tungsten filament	CFL	LED
power rating	60 W	14 W	10 W
average cost per bulb (£)	1	2	4
average lifespan (hours)	1200	8000	25 000

Table P5.09: Data for different light bulbs.

SUMMARY

Magnets have a north pole and a south pole.
Like poles repel and unlike poles attract.
Magnetic elements can be magnetised. These include iron, cobalt and nickel.
A permanent magnet can attract unmagnetised magnetic materials by inducing magnetism in them.
A hard magnetic material like steel is difficult to magnetise and demagnetise.
A soft magnetic material like soft iron is easy to magnetise and demagnetise.
A magnetic field is a region of space around a magnet or electric current in which a magnet will feel a force.
A magnetic field line is the line (direction) of force on the north pole of the magnet, which is why a magnet (for example, a compass needle) lines up with it.
An electromagnet (or solenoid) is a magnet created when a current is passed through wire, which is usually shaped into a coil.
The advantages of an electromagnet over a permanent magnet are that its strength can be changed, it can be switched on and off, and it can be reversed.
There are two types of charge: positive and negative.

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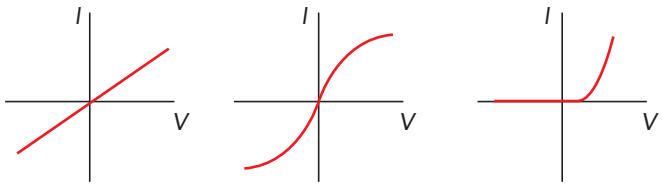
CONTINUED

Like charges repel, opposite charges attract.
Conductors allow charge to flow. Insulators do not allow charge to flow.
Conductors (for example, metals) allow electric current to flow through them. Insulators (for example, plastic) resist the flow of current.
Metals are good conductors. Most non-metals are insulators.
Insulators can be charged by friction, which causes the loss or gain of electrons.
Insulators are materials in which electrons are fixed in place. Conductors have free electrons.
An electric field is the area around a charged object in which a charge will experience a force.
An electric current will flow only if there is a supply of energy (for example, a battery) to push it around a complete circuit.
Current is a flow of electric charge (for example, electrons) in a circuit.
Electric current is measured, in amperes or amps (A), by an ammeter connected into a circuit in series.
Current is the rate at which electric charge (for example, electrons) passes a point in a circuit: $I = \frac{Q}{t}$
Energy can be stored in different ways and can be transferred between stores.
Voltage is measured in volts (V) by a voltmeter connected in parallel across the component.
The p.d. across a cell is called the electromotive force (e.m.f.).
The resistance of a component is a measure of how hard it is for current to flow through the component. It is measured in ohms (Ω).
The resistance of a circuit component is the p.d. across it divided by the current passing through it. Resistance is given by the equation $R = \frac{V}{I}$ and it can be found by experiment.
The resistance of a wire is proportional to its length and inversely proportional to its cross-sectional area.
The current–voltage graphs for different components have characteristic shapes:    constant resistor filament lamp diode
Electric circuits transfer energy from the battery or power source to the circuit components and then the surroundings.
Electrical power is current multiplied by voltage ($P = IV$) and electrical energy is $E = IVt$.
Electrical energy can be measured in joules or in kilowatt-hours.

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PRACTICE QUESTIONS

1 A positively charged rod is suspended so it can move freely. A negatively charged rod is brought close to it. Identify what will happen to the positive rod.

A It will repel.

B Nothing will happen.

C It is not possible to predict what will happen from the information given.

D It will attract. **[1]**

2 Identify which statement describes how an object becomes positively charged.

A It gains positive charge.

B It loses positive charge.

C It gains negative charge.

D It loses negative charge. **[1]**

3 **Identify** *two* magnetic materials. **[2]**

4 **a** Identify the particles which carry currents in a metallic conductor. **[1]**

b **State** the charge on these particles. **[1]**

[Total: 2]

5 To charge a camera flash, a current of 400 mA flows from a 6.0 V battery for 1.7 s.

Calculate the energy transferred in joules. **[2]**

6 Wire A has a resistance of 20 Ω. Wire B is twice as long as wire A and its cross-sectional area is twice that of A.

Calculate the resistance of wire B. **[2]**

7 **a** **Sketch** the field lines you would expect to see around this bar magnet.

[2]

b **Explain** how you could use a plotting compass to investigate the magnetic field around a bar magnet. **[3]**

c Identify the difference between a magnetically soft and a magnetically hard material. **[1]**

[Total: 6]

8 A student combs his hair with a plastic comb. The comb becomes negatively charged.

a Explain how this happens. **[2]**

b **Give** the name of the particles which are transferred. **[1]**

c The student notices his hair is now standing on end. Explain why this happens to his hair. **[2]**

[Total: 5]

COMMAND WORDS

identify: name/select/recognise.

state: express in clear terms.

calculate: work out from given facts, figures or information.

sketch: make a simple freehand drawing showing the key features, taking care over proportions.

explain: set out purposes or reasons/make the relationships between things clear/say why and/or how and support with relevant evidence.

COMMAND WORD

give: produce an answer from a given source or recall/memory.

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CONTINUED

9 A student wanted to measure the resistance of a filament lamp. She used an ammeter, a cell, a lamp and a voltmeter.

a Sketch the circuit she built. **[2]**

b The ammeter reading is 1.5 A and the voltmeter reading is 6 V. Calculate the resistance of the lamp. **[2]**

c The student replaces the cell with a 12 V battery. State what will happen to the ammeter reading. **[1]**

[Total: 5]

10 An electric iron has a power rating of 1200 W. It is used for 30 minutes.

a Calculate the energy used in joules. **[2]**

b Calculate the energy used in kilowatt-hours. **[2]**

c The iron is plugged in to a 230 V mains supply. Calculate the current which flows through the iron. **[2]**

[Total: 6]

SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
name the two types of charge	P5.01			
say how objects with identical or opposite charges affect each other	P5.01			
explain how charging by friction happens by describing what happens to the electrons	P5.01/6			
name the unit of electrical charge	P5.01			
define what is meant by an electric field	P5.01/6			
state what a current is made of	P5.02			
recall the units of current, voltage and resistance	P5.02			
recall what devices measure current and voltage and know how to connect them into a circuit	P5.02			
recall and use the equation that relates current, charge and time	P5.02			
recall the name given to the voltage across a cell or battery	P5.02			
define resistance and give its unit	P5.02			
recall and use the equation that relates resistance, current and voltage	P5.02			

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CONTINUED

I can	See topic . . .	Needs more work	Almost there	Confident to move on
recall and use the relationships that relate the resistance of a wire to its length and cross-sectional area	P5.02			
sketch and explain the current–voltage graph for a resistor of constant resistance	P5.02			
understand that electric circuits transfer energy from the battery or power source to the circuit components and then the surroundings	P5.02			
distinguish between conductors and insulators and give examples of each	P5.02/6			
recall and use the equations for electric power and energy	P5.03			
state the two units which are used for electrical energy	P5.03			
recall the names of the two poles of a magnet and state how different poles affect each other	P5.05			
identify common magnetic materials	P5.05			
recall the difference between magnetic and non-magnetic materials and give examples of both	P5.05			
account for induced magnetism	P5.05			
recall examples of hard and soft magnetic materials and the difference between them	P5.05			
draw the pattern of magnetic field lines around a bar magnet	P5.05			
describe the differences between electromagnets and permanent magnets.	P5.05			

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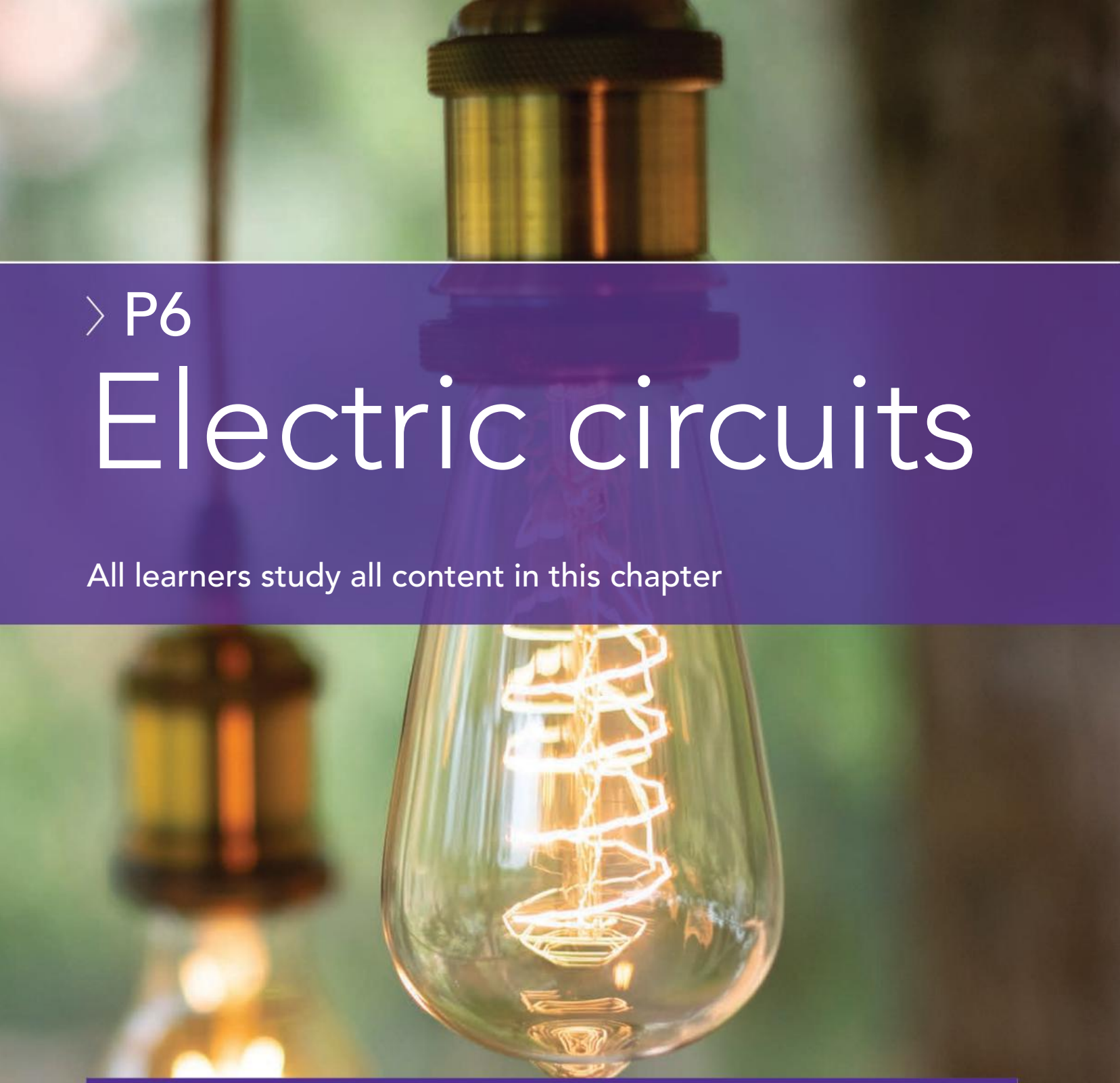

P6 Electric circuits

All learners study all content in this chapter

IN THIS CHAPTER YOU WILL:

- draw and interpret circuit diagrams
- describe how current and resistance vary in different circuits
- construct and use series and parallel circuits
- learn how to calculate resistances, currents and voltages in circuits
- highlight the hazards of using electricity and describe and explain electrical safety measures.

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BEFORE YOU START

Spend two minutes thinking about these questions before comparing notes with the person sitting next to you. Add to, or correct, your own work. Be prepared to share your thoughts with the class.

1 How can you tell a series circuit apart from a parallel circuit?

2 Why does less current flow through each lamp when there are two lamps in series, compared with two lamps in parallel?

3 Why does more total current flow when there are two lamps in parallel, compared with two lamps in series?

SCIENCE IN CONTEXT P6.01

How close are we to creating artificial intelligence?

In 1800, Alessandro Volta invented the first battery and the first electric circuit. Development of the first electric light bulb followed almost immediately, though it was almost a century before it was good enough to sell. Electric lighting became the first of many applications of electric circuits. For example, electric circuits can transport electricity from where it is generated to where it is used.

Electric circuits can also be used to automate tasks, such as switching on a lamp when it gets dark, and transferring energy in a light bulb in the process.

The semiconductor transistor is perhaps the most important invention of the last century because it is much smaller and cheaper than the device (called a valve) that it replaced. Without transistors we would not have smartphones or personal computers as these are based on miniature electric circuits that use millions of transistors. If smartphones were made using the old technology, they would fill a room. Making computers smaller means they can be used to control more appliances.

Driverless cars will be controlled by computers, which will make decisions based on programs written by people. However, an alien might think the cars are automatons (making decisions by themselves). Robots (Figure P6.01) already exist that could be mistaken for artificial intelligence (machines that can think for themselves). Some scientists worry that we are close to creating artificial intelligence, perhaps by accident, which might be a threat to our future existence. The challenge for society is to ensure artificial intelligence is used in beneficial ways.

Figure P6.01: Rico's combat robot from the science fiction film, *Judge Dredd*, 1995.

Discussion questions

1 Draw a table with two columns. In the left column, write down the names of ten household appliances (such as 'television') that rely on electricity, and, therefore, include an electric circuit. In the right-hand column, write down the names of appliances that do not need electricity. What do you notice?

2 Try describing what our world might be like if electricity had not been discovered.

3 What are the potential positives and negatives of automation and artificial intelligence?

P6.01 Describing circuits

Circuit diagrams and circuit components

Circuits are represented using circuit diagrams. Electrical components have symbols which are used worldwide, so that electrical engineers who speak different languages can read each other's circuit diagrams.

Table P6.01 describes the function of some of the components you will be using.

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Component	How the component behaves in a circuit
cell	supplies the voltage to make current flow in a circuit transfers its store of chemical energy to electrical energy
lamp	transfers electrical energy to light and heat
motor	transfers electrical energy to movement
battery	more than one cell working together to increase the voltage or the time the current can be delivered for
power supply	usually plugged into the mains to supply electric current
a.c. power supply	plugged into the mains, supplies alternating current
switch	can be open to stop current flowing or closed to allow current to flow
fixed resistor	controls the amount of current flowing
variable resistor	resistance can be varied to control current
heater	transfers electrical energy to heat energy
generator	transfers kinetic energy to electrical energy
light emitting diode (LED)	allows current to flow in only one direction emits light when current is flowing through it
transformer	changes the voltage of an electrical supply step up transformers increase voltage, step down transformers decrease voltage
magnetising coil	a coil of wire, usually with a soft iron core, which becomes magnetised when current flows through it

Table P6.01: The uses of some electrical components.

Figure P6.02 shows the most common electric symbols.

Series circuits

Figure P6.03 shows a series circuit. A series circuit has only one loop, so current can only flow one way. As current is a flow of charge, and charge is not used up, the current is the same at all points in a series circuit. Ammeters placed at different points in a series circuit will all give the same reading.

If a series circuit is broken at any point, for example if a lamp is unscrewed, then no current can flow in the circuit.

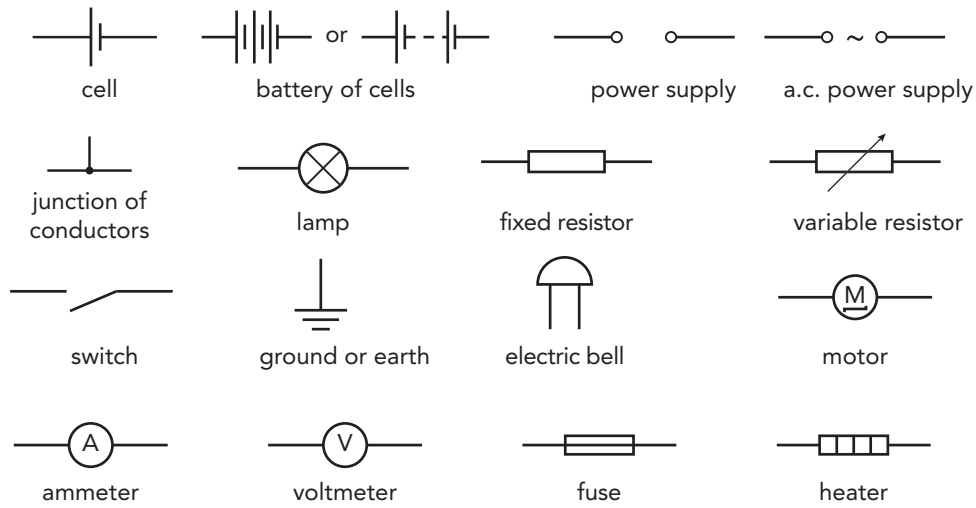

Figure P6.02: Electrical components and their symbols.

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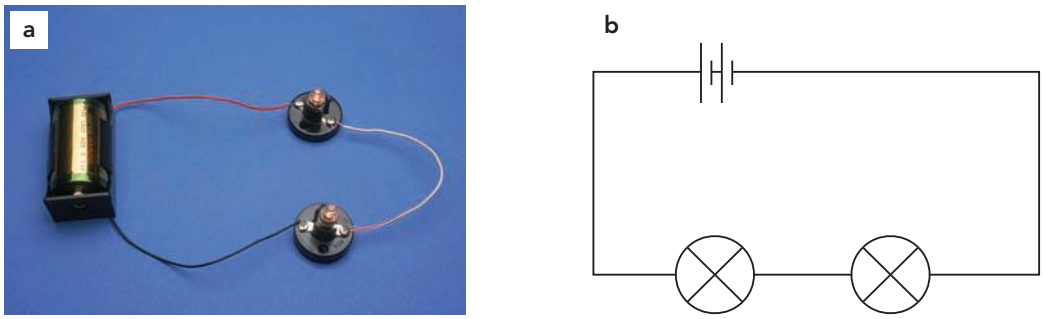

Figure P6.03 a: A series circuit. **b:** The circuit diagram for the series circuit. Note that wires are drawn as straight lines.

Parallel circuits

Figure P6.04 shows a parallel circuit. A parallel circuit consists of more than one loop. The current leaves the cell and splits when it reaches the junction. The different paths are sometimes called branches of the circuit. Some current flows through the first lamp and some through the second. The current leaving the cell is bigger than the current which flows through each lamp.

Looking at the circuit diagram, it is clear that unscrewing one lamp will not stop current flowing to the other lamp, as a complete loop of circuit still exists. This is why house lights use parallel circuits, allowing lamps to be controlled independently.

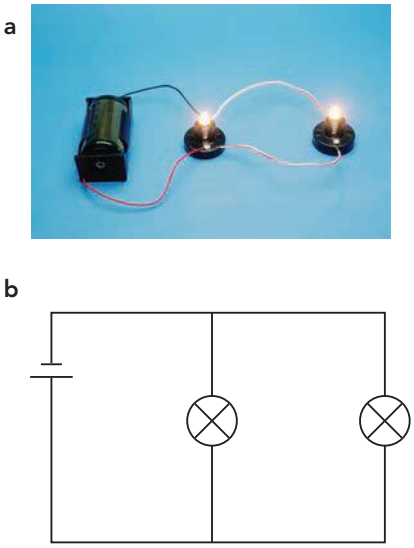

Figure P6.04 a: A parallel circuit. **b:** The circuit diagram for the parallel circuit.

P6.02 Resistors

A **resistor** (Figure P6.05) can be used to control the amount of current flowing around a circuit. A resistor has two terminals, so that the current can flow in one end and out of the other. They may be made from metal wire (usually an alloy – a mixture of two or more metals with a high resistance) or from carbon. Carbon (like the graphite in a pencil) conducts electricity, but not as well as most metals.

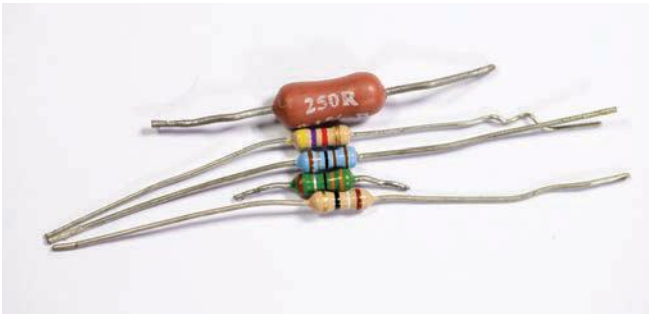

Figure P6.05: A selection of resistors. Some have colour-coded stripes to indicate their value, and others use a number code.

A **variable resistor** can be used to alter the current flowing in a circuit by changing the resistance of the resistor. Most variable resistors consist of a coil of resistance wire with a sliding contact. As the contact is moved, the amount of wire the current flows through changes and so does the resistance. Figure P6.06 shows two common variable resistors.

KEY WORDS

resistor: a component in an electric circuit whose resistance decreases the current flowing.

variable resistor: a resistor whose resistance can be changed, for example by turning a knob or moving a slider.

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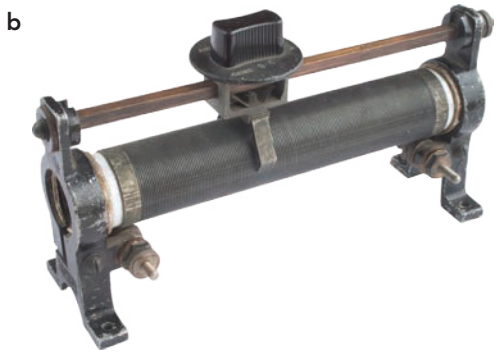

Figure P6.06 a: A variable resistor used as a dimmer switch. Turning the dial increases the resistance. This decreases the current so the light will be dimmer. **b:** A variable resistor known as a rheostat which is often used in school laboratories. Sliding the top contact changes the amount of wire the current must flow through.

Resistors in series

If several resistors are connected in series, then the current must flow through them all, one after another. The combined resistance, R, in the circuit is simply the sum of all the separate resistances. For three resistors in series (Figure P6.07), the equation for their combined resistance is:

$$R = R_1 + R_2 + R_3$$

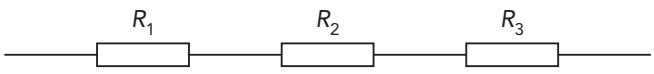

Figure P6.07: The combined resistance of resistors in series is found by adding the individual resistances.

WORKED EXAMPLE P6.01

Calculate the combined resistance of the three resistors and use this to calculate the current in the circuit shown in Figure P6.08.

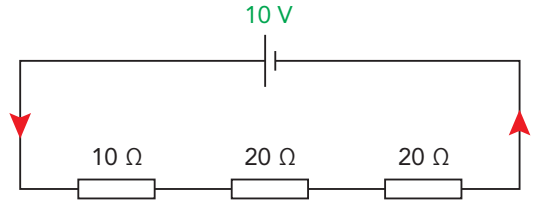

Figure P6.08: Resistors in series.

Step 1: Combined resistance = $R = R_1 + R_2 + R_3$

Combined resistance = $10\,\Omega + 20\,\Omega + 20\,\Omega = 50\,\Omega$

Step 2: Use the equation $I = V \div R$ to calculate the current

$I = V \div R$

$I = 10 \div 50 = 0.2\,\text{A}$

Answer

The current all around the circuit is 0.2 A.

Resistors in parallel

The effective resistance of two resistors connected in parallel is less than either resistance by itself. This is because it is easier for the current to flow. Adding an extra resistor gives current an alternative route, so more current can flow. You can see this for two resistors in parallel in Figure P6.09 it is easier for current to flow through the combination of resistors than through either resistance on its own.

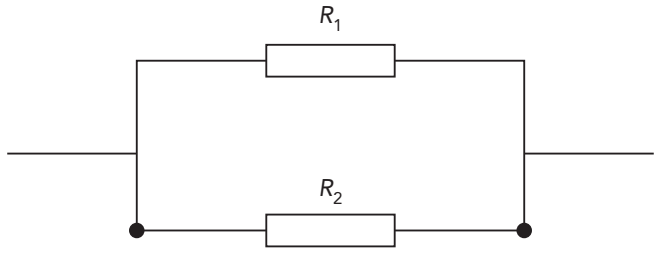

Figure P6.09: Two resistors connected in parallel. Adding an extra path for current decreases the overall resistance.

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Table P6.02 summarises what you have learnt about series and parallel circuits.

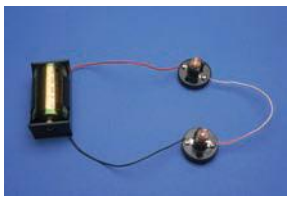
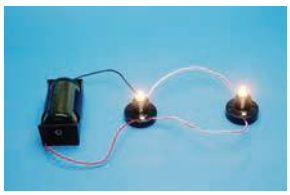
Series circuit	Parallel circuit
	
a switch placed anywhere in the circuit will control all the components	the components can be controlled individually by separate switches placed in the branches of the circuit
consists of one loop	consists of more than one loop
the current is the same at all points around the circuit	the current from the source is greater than the current through either resistor
the combined resistance is equal to the sum of the resistances	the combined resistance of two resistors is less than the resistance of either resistor

Table P6.02: Comparison between series and parallel circuits.

Questions

P6.01 **a** Draw the circuit symbol for a resistor.

b Draw the circuit symbol for a variable resistor.

P6.02 Three resistors are connected in series with a battery, as shown in Figure P6.10.

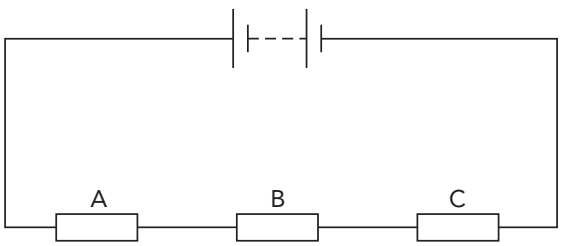


Figure P6.10: Three resistors in series with battery.

Resistor A has the greatest resistance of the three. The current through A is 1.4 A. What can you say about the currents through B and C?

P6.03 What is the combined resistance of three 30 Ω resistors connected in series?

P6.04 What are the advantages of connecting lamps in parallel in a lighting circuit?

P6.03 Circuit calculations

Voltage in series circuits

When resistors are connected in series with each other in a circuit with a power supply, there is a p.d. across each resistor. As the current through each resistor is the same, we can calculate the p.d. across each resistor using $V = I \times R$.

Using the circuit from Worked example P6.01 we can see the p.ds across the resistors are 2 V, 4 V and 4 V, as shown in Figure P6.11.

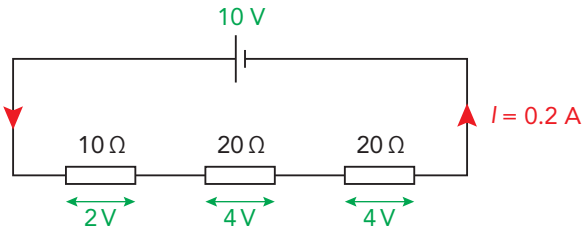


Figure P6.11: Values of current and p.d. in a series circuit. The same current, *I*, flows through each of the three resistors.

From this example we can see that adding up the p.ds across the three separate resistors gives the p.d. of the power supply. In other words, the p.d. of the supply is shared between the resistors. We can write this as an equation:

$$V = V_1 + V_2 + V_3$$

Or, for this example:

$$10\,\text{V} = 2\,\text{V} + 4\,\text{V} + 4\,\text{V}$$

Strings of festive lights are often wired together in series. This is because each bulb works on a small voltage. If a single bulb was connected to the mains supply, the p.d. across it would be too great. By connecting them in series, the mains voltage is shared out between them. There is a disadvantage; if one bulb fails (its filament breaks), they all go out. This is because there is no longer a complete circuit for the current to flow around.

WORKED EXAMPLE P6.02

Three 5.0 Ω resistors are connected in series with a 12 V power supply. Calculate the combined resistance of the three resistors, the current that flows in the circuit, and the p.d. across each resistor.

Step 1: Draw a circuit diagram and mark on it all the quantities you know. Add arrows to show how the current flows (Figure P6.12).

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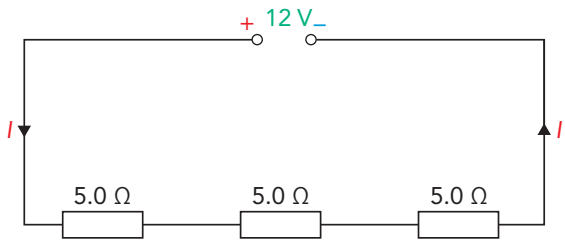

Figure P6.12: Sketch diagram.

Step 2: Calculate the combined resistance.

$R = R_1 + R_2 + R_3$

$R = 5.0\,\Omega + 5.0\,\Omega + 5.0\,\Omega$

$R = 15\,\Omega$

Step 3: Calculate the current flowing. A p.d. of 12 V is pushing current through a resistor of 15 Ω total resistance. So:

$$\text{current } I = \frac{V}{R}$$

$$= \frac{12\,\text{V}}{15\,\Omega}$$

$$= 0.8\,\text{A}$$

Step 4: Calculate the p.d. across an individual 5.0 Ω resistor when a current of 0.8 A flows through it.

p.d. $V = IR = 0.8\,\text{A} \times 5.0\,\Omega = 4.0\,\text{V}$

Note that the 12 V of the supply is shared out equally between the resistors, since each has the same resistance. So, we could have worked out the p.d. across an individual resistor without knowing the current (12 V ÷ 3 = 4 V).

Answer

The combined resistance of the three resistors is 15 Ω, the current that flows in the circuit is 0.8 A, and the p.d. across each resistor is 4.0 V.

Voltage in parallel circuits

The voltage across each branch in a parallel circuit is the same as the voltage of the supply. Each branch of the circuit works independently, with the same voltage as the supply. Household circuits are connected in parallel. This means that each appliance receives the full mains voltage and can operate independently. Figure P6.13 shows that the lamps light equally brightly in **a** and **b** as the voltage across each branch of the circuit is equal to the voltage of the supply.

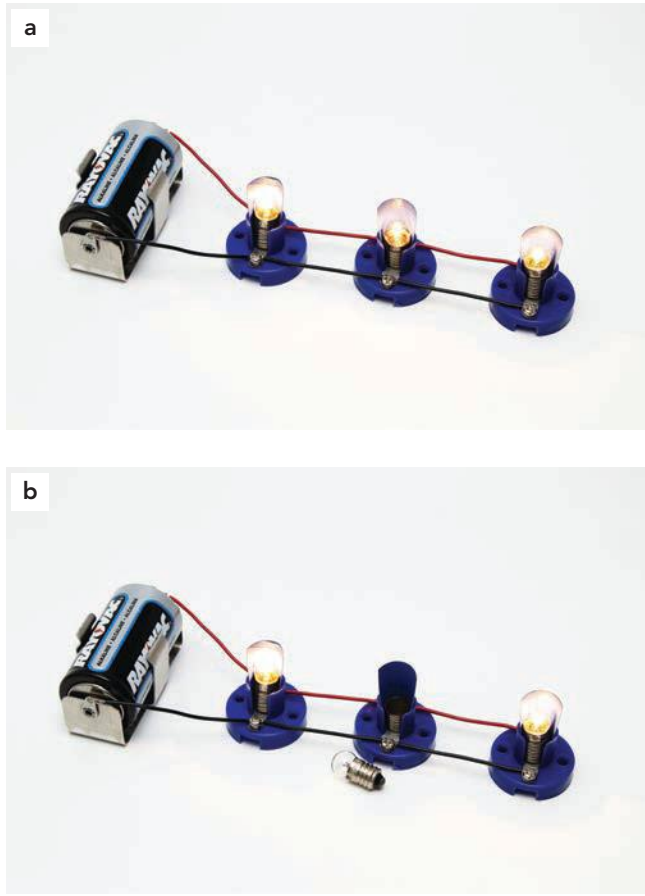

Figure P6.13: The lamps in this circuit all have the full voltage of the cell connected across them. In diagram **a**, all three lamps are fully lit. In diagram **b** one lamp is removed, but the others have the same brightness as in a.

Current in parallel circuits

Imagine cars arriving at a junction in the road: the number of cars leaving the junction must equal the number of cars that arrived.

In the same way, electric charge flowing into and out of a junction must be equal. Electrons in an electric circuit cannot appear from nowhere or disappear, so the amount of charge flowing into and out of the junction each second are the same. The current is the amount of charge flowing each second. This means that the total current coming into a junction must equal the total current leaving the same junction.

Therefore, when current divides up to pass through the branches of a parallel circuit, the current entering the junction is equal to the sum of the currents in the separate branches.

In Figure P6.14, 0.7 A flows into the junction. The total after it splits is still 0.7 A (0.5 + 0.2). When the two branches rejoin, the total is still 0.7 A.

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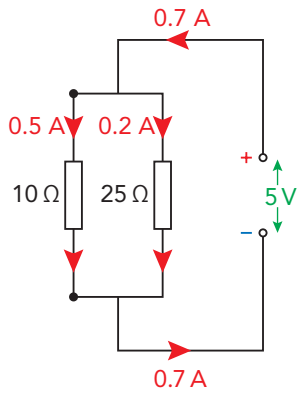

Figure P6.14: 0.7 A leaves the supply. The current splits but the total remains the same: 0.5 + 0.2 = 0.7.

Resistance in parallel circuits

We have seen that the resistance of two resistors in parallel is less than either of the individual resistances. To calculate the combined resistance, R, for two resistors in parallel, we use this equation:

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

There are two ways to calculate this type of sum: either use a calculator, or add up the fractions by finding their lowest common denominator. Worked example P6.03 shows how to use this equation, and how to work out the sum by finding the lowest common denominator.

WORKED EXAMPLE P6.03

One 10 Ω resistor and a 30 Ω resistor are connected in parallel with a 12 V power supply. Calculate:

a the effective resistance of the two resistors

b the current through each resistor

c the current flowing from the power supply.

Step 1: Sketch a circuit diagram and mark on it all the quantities you know (Figure P6.15). Add arrows to show how the current flows, like this:

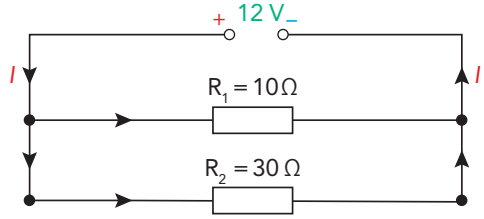

Figure P6.15: Sketch circuit.

CONTINUED

Step 2: Calculate the effective resistance.

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

$$\frac{1}{R} = \frac{1}{10\,\Omega} + \frac{1}{30\,\Omega}$$

$$\frac{1}{R} = \frac{4}{30\,\Omega}$$

$$R = 7.5\,\Omega$$

Step 3: Each resistor has a p.d. of 12 V across it. Now we can calculate the currents using the equation:

$$I = \frac{V}{R}$$

$$\text{current } I \text{ through } 10\,\Omega \text{ resistor} = \frac{12\,\text{V}}{10\,\Omega} = 1.2\,\text{A}$$

$$\text{current } I \text{ through } 30\,\Omega \text{ resistor} = \frac{12\,\text{V}}{30\,\Omega} = 0.4\,\text{A}$$

Notice that, as you might expect, the smaller (10 Ω) resistor has a bigger current flowing through it than the larger (30 Ω) resistor.

Step 4: The current, I, flowing from the supply is the sum of the currents flowing through the individual resistors.

I = 1.2 A + 0.4 A = 1.6 A

Note: we could have reached the same result using the effective resistance (7.5 Ω) of the circuit that we found in step 2:

$$I = \frac{V}{R} = \frac{12\,\text{V}}{7.5\,\Omega} = 1.6\,\text{A}$$

This is a useful way to check that you have calculated the effective resistance correctly. Current divides in a parallel circuit, but the total amount must remain the same. Electrons cannot just disappear.

Answers

a The two resistors together have an effective resistance of 7.5 Ω.

b The 10 Ω resistor has a current of 1.2 A flowing through it. The 30 Ω resistor has a current of 0.4 A flowing through it.

c There is a 1.6 A charge flowing from the power supply.

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Questions

P6.05 Use the idea of resistors in series to explain why a long wire has more resistance than a short wire (of the same thickness and material).

P6.06 Use the idea of resistors in parallel to explain why a thick wire has less resistance than a thin wire (of the same length and material).

P6.07 A 15.0 Ω resistor is connected in series with a 30.0 Ω resistor and a 15.0 V power supply.

- **a** Calculate the current flowing around the circuit.
- **b** Which resistor will have the larger share of the p.d. across it?

P6.08 One 6 Ω resistor and one 4 Ω resistor are connected in parallel with a 6 V power supply.
Calculate:

- **a** the effective resistance of the two resistors
- **b** the current through each resistor
- **c** the current flowing from the power supply.

ACTIVITY P6.01

Check the theory

In this activity you will plan and carry out experiments to provide evidence to support the theory you have learnt about electrical circuits.

Choose one or more of the options below. Draw a diagram to show what you will be doing. Make a prediction based on the theory and then conduct your experiment.

- The current is the same at all points in a series circuit.
- The combined resistance of two resistors in series is the sum of the individual resistors.
- Two resistors in parallel have less resistance than either of the individual resistors.
- The sum of the p.ds across resistors in series is equal to the p.d. of the power supply.
- The total current entering a junction in a circuit is equal to the total current leaving the circuit.

Present your results to another group. State the theory you are trying to support. Include a circuit diagram, your table of results and your conclusion.

Peer assessment

How convinced are you by the data the other group presented to you? Give them a percentage rating. 100% means you are totally convinced.

If you are less than 100% sure, suggest extra experimental work which would make the results more convincing.

REFLECTION

How confident are you in building a circuit from a circuit diagram?

Which circuits are most difficult?

What can you do to make this process easier?

P6.04 Electrical safety

There are two main risks to consider in using electricity: shocks and fires.

Mains electricity is hazardous, because of the large voltages involved. Mains voltages are different in different countries, but usually 110 V or 230 V. If you come into contact with a bare wire at these voltages, you could receive a fatal electric shock.

When current flows through a component, it will become hot, as you can see in the filament lamp in Figure P6.16. If the current is too high, the heat produced may cause a fire.

Figure P6.16: This lamp produces light and heat by passing current through a resistance wire.

Here, we will look at some ways to ensure we use electricity safely.

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Electrical cables

The cables that carry electric current around a house are carefully chosen. Figure P6.17 shows some examples. For each, there is a maximum current that it is designed to carry. A 5 A cable (Figure P6.17a) is relatively thin. This might be used for a lighting circuit, since lights do not require much power, so the current flowing is relatively small. The wires in a 30 A cable (Figure P6.17c) are much thicker. This might be used for an electric cooker, which requires much bigger currents than a lighting circuit.

The wires in each cable are insulated from one another, and the whole cable has more protective insulation around the outside. If this insulation is damaged, there is a chance that the user will touch the bare wire and receive an electric shock.

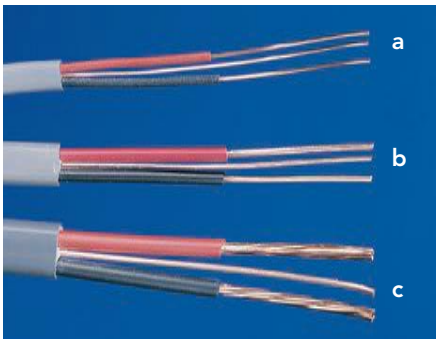

Figure P6.17: Cables of different thicknesses are chosen according to the maximum current that they are likely to have flowing through them. **a:** 5 A. **b:** 15 A. **c:** 30 A. Each cable has live, neutral and earth wires, which are colour coded. In these cables, the earth wire does not have its own insulation.

Another hazard can arise if an excessive current flows in the wires. They will overheat and the insulation may melt, causing it to emit poisonous fumes or even catch fire. Thus it is vital to avoid using appliances that draw too much current from the supply. **Fuses** help to prevent this from happening.

KEY WORD

fuses: a device that breaks the circuit if the current exceeds a certain value; it is a piece of metal wire that melts when too much current flows through it.

Fuses

Fuses are included in circuits to stop excessive currents from flowing. This protects the circuit and the cabling for a domestic appliance. A fuse contains a thin section of wire, designed to melt and break if the current gets above a certain value. Usually, fuses are contained in cartridges, which makes it easy to replace them, but some fuses use fuse wire, as shown in Figure P6.18. The thicker the wire used for the fuse, the higher the current that is needed to make it melt (or blow). A fuse represents a weak link in the electricity supply chain. Replacing a fuse is preferable to having to rewire a whole house.

Figure P6.18: Cartridge fuses and fuse wire. The thicker the wire, the higher the current that causes it to melt.

It is important to choose a fuse of the correct value in order to protect an appliance. The current rating of the fuse should be just above the value of the current that flows when the appliance is operating normally (see Worked example P6.04).

WORKED EXAMPLE P6.04

A 2 kW heater works on a 230 V mains supply.
The current flowing through it in normal use is 8.7 A.

Which of the following current ratings would a suitable fuse have?

- 3 A
- 13 A
- 30 A

Step 1: The 3 A fuse has a current rating that is too low, and it would melt as soon as the heater was switched on.

Step 2: The 30 A fuse would not melt, but it is unsuitable because it would allow an excessive current (say, 20 A) to flow, which could cause the heater to overheat.

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CONTINUED

Step 3: The 13 A fuse is the correct choice, because it has the lowest rating above the normal operating current.

Answer

13 A

Damp conditions

When using electricity, it is important to avoid damp or wet conditions. Water is an electrical conductor. So, for example, if your hands are wet when you touch an electrical appliance, the water may provide a conductive path for current to flow from a live wire through you to earth. This could prove fatal.

Multi-plug adapters

The number of electrical appliances people use in their homes is increasing. The safest option is to have more wall sockets fitted. The alternative is to use multi-plug adaptors that allow us to plug more than one device into the same wall socket. Multi-plug adaptors come in two main varieties. The safer option is to use a multi-way bar extension, which comes as a bank of sockets on the end of an extension lead that can be plugged into a wall socket, as shown in Figure P6.19. These are generally fitted with a fuse to match the wall socket (13 A in the UK).

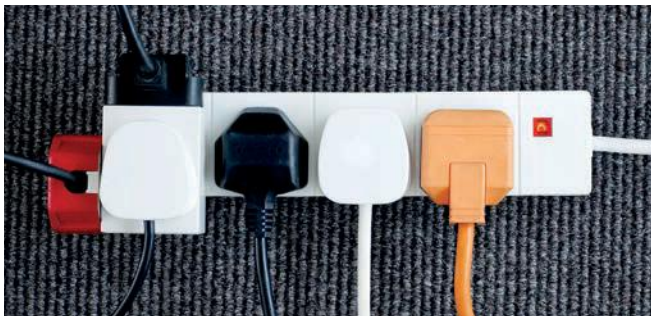

Figure P6.19: A multi-way bar extension with four available sockets and white electrical cable (on the right). There is a block adapter with three sockets plugged into the left-hand end of the extension. Plugging multi-plug adapters together should be avoided.

Be wary of block adaptors, which are plugged directly into a wall socket. They usually have a cubic shape and two or more sockets (see the left-hand side of Figure P6.19). These are less likely to contain a fuse so there is an increased danger that a current will exceed the rating of the wall socket. Overloading the socket in this way increases the chance that it, and the plug, will heat up and catch fire.

It is important not to exceed the current rating of any part of the system. Imagine there are four devices, each drawing a current of 3 A. This would not overload a wall socket so they could be plugged into the same wall socket via a fused multi-plug adaptor. However, if an extension is rated at 10 A, no more than three of its sockets should be used, even if more sockets are available. Avoid using a block adapter that does not have a fuse. Never join multi-plug adapters together. For example, do not plug a block adapter into an extension as shown in Figure P6.18.

Trip switch

A **trip switch** can replace a fuse. The switch trips and breaks the circuit when the current flowing through the trip switch exceeds a certain value. Some modern house wiring systems use trip switches instead of fuses in the fuse box (Figure P6.20). You have probably come across trip switches on laboratory power supplies. If too much current starts to flow, the supply itself might overheat and be damaged. The trip switch jumps out, and you may have to wait a short while before you can reset it.

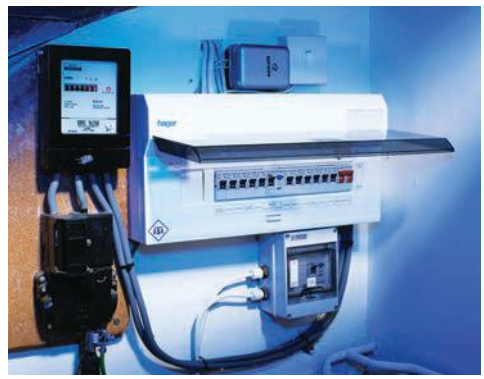

Figure P6.20: This is where the mains electricity supply enters a house. On the left is the meter. The white box contains a trip switch for each circuit in the house.

Earth wire or double insulation

We have already seen why the insulation on wires is important – to prevent fires or an electric shock. This is because there is a chance that current will flow between two bare wires (a short circuit), or between one bare wire and any piece of metal it comes into contact with. This is why the metal case of an

KEY WORDS

trip switch: safety device that includes a switch that opens (trips) when a current exceeds a certain value.

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electrical appliance is **earthed** by connecting it to the earth wire. The earth wire provides a low resistance electrical path to the ground and reduces the chances of a fatal electric shock.

A mains circuit consists of a live (or line) wire, a neutral wire and an earth wire. These are carried around buildings as part of the ring mains and we can plug into it via wall sockets.

The plug which connects an appliance to the mains has three insulated wires, colour coded so that people can wire up plugs and appliances safely. The colours vary around the world. Figure P6.21 shows the type of plug used in the UK. The live wire (coloured brown) carries the electrical current from the wall socket to the electrical appliance and the neutral wire (blue) carries the current back to the socket. There is usually also an earth wire (yellow and green stripes).

Figure P6.21: Inside an electrical plug.

Figure P6.22a shows the wiring when there is no fault. The earth wire is connected between the casing of the appliance and the earth pin of the plug. This is a schematic diagram (to show you what is happening). The coloured wires are all inside the electrical cable and the connection to the metal case is actually made from inside the appliance.

Imagine that there is now a fault (Figure P6.22b) and the live wire touches the metal case. The case will now be at the mains voltage (230 V in the UK). Anyone touching the casing could receive a fatal shock. However, the earth wire provides a low resistance path to ground. You can trace the path of the current with your finger. It passes through the live pin at the bottom right of the plug, along the live wire (through the fuse) to the metal casing and then along the earth wire. Because the resistance of this path is low and the voltage is high, a high current will pass through the fuse, which will almost instantly melt, stopping any current flowing to the appliance.

Electrical appliances that are **double insulated** do not need an earth connection (only two wires are wired into the three-pin plug). Even if there are metal parts on the outer casing, the electrical circuit for the appliance is inside a case underneath, which is made from electrically insulating material (for example, plastic) so that an electric current cannot pass

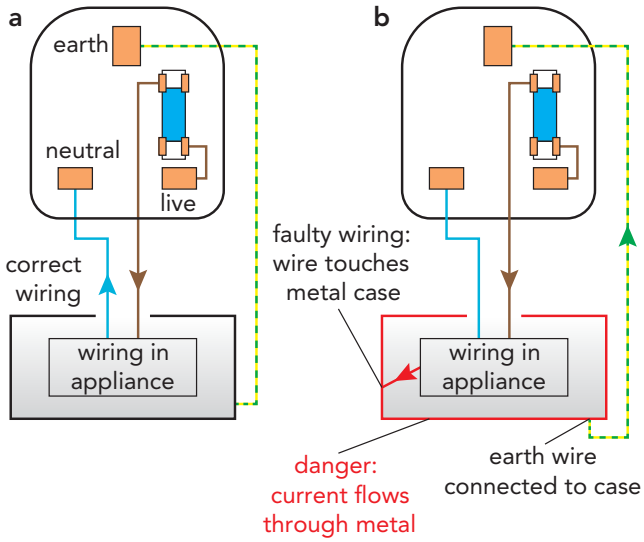

Figure P6.22 a: How the current flows from the live pin of the plug along the live wire (brown) to the appliance and back to the plug and socket along the neutral wire (blue). **b:** When there is a fault and a bare wire in the appliance touches the metal casing, the current flows through the earth wire (green and yellow stripes) instead of the neutral wire, and the fuse melts because a large current flows along this low resistance path.

through it. There is no way that a live conductor could touch the outer case. This means that there is no way that somebody touching the outer case could be electrocuted. When the symbol shown in Figure P6.23 is stuck to the casing of an electrical appliance, this shows that it is double insulated.

Figure P6.23: The symbol for double insulation. If you see this stuck to the casing of an electrical appliance then it will not need an earth wire.

KEY WORDS

earthed: when the case of an electrical appliance is connected to the earth wire of a three-pin plug; the earth wire is electrically connected to the ground to prevent current passing through anyone touching a faulty appliance.

double insulated: when the electric circuit for an electrical appliance is placed inside a case made from an electrical insulator so that it is impossible for a live wire to touch the outer casing.

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Questions

P6.09 Name the *two* main types of multi-plug adapters.

P6.10 What is often missing from a block adapter that makes it more dangerous to use than a multi-plug adapter?

P6.11 Why is it important not to overload a wall socket or any multi-plug adapter plugged into the mains?

P6.12 How does a fuse work?

P6.13 In normal use, a current of 3.5 A flows through a hair dryer. Choose a suitable fuse from the following: 3 A, 5 A, 13 A, 30 A. Explain your choice.

P6.14 **a** Why are fuses fitted in the fuse box of a domestic electricity supply?

b What device could be used in place of fuses?

P6.15 What hazards can arise when the current flowing in an electrical wire is too high?

P6.16 Explain how an earth wire makes an electrical device safe.

P6.17 Why should a fuse be connected to the live wire and not the earth wire or neutral wire?

P6.18 What is double insulation?

PROJECT P6.01 THE SHOCKING TRUTH ABOUT ELECTRICAL SAFETY

Electricity in the home can be fatal. Poor wiring and use of the wrong fuse can lead to electric shocks or fires. Your task is to design a leaflet to be delivered to homes to help people avoid these dangers.

Your leaflet should have visual impact. Where possible, use labelled illustrations instead of text. Do not exceed 100 words.

Highlight the dangers of using:

- household electrical appliances in damp conditions or with damaged insulation
- multi-plug adapters (especially those that do not include a fuse); and of joining multi-plug adapters together.

Emphasise the importance of using the correct fuse rating. Explain how to choose the correct fuse for an appliance.

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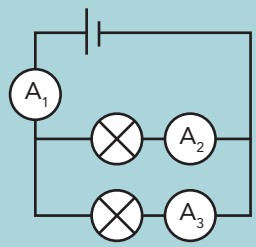
SUMMARY

A resistor can control the amount of current flowing around a circuit.
Resistors in series are connected end-to-end.
For resistors in series, the total resistance is equal to the sum of the resistors.
The current is the same at all points around a series circuit.
The voltage of the source is shared between resistors in a series circuit.
For resistors arranged in parallel, the effective resistance is less than the value of the smallest resistor.
To calculate the effective resistance, R, for two resistors in parallel, we use the equation $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$
The current from the source divides to pass through parallel resistors.
The current from the supply is the sum of the currents flowing through parallel resistors: $I = I_1 + I_2 + I_3$
Lights in a house are arranged in parallel so that each has the supply voltage across it and can be controlled by its own switch.
Excessive current through a wire can melt insulation, causing it to emit poisonous fumes or catch fire.
Using multi-plug adapters (multi-way bar extensions and block adapters) increases the risk of overloading plugs and sockets.
A fuse contains a thin section of wire, designed to melt and break the circuit if the current gets above a certain value.

PRACTICE QUESTIONS

1 **Identify** the correct statement about the readings on the ammeters.



A all three ammeters have the same reading.
B A_1 has the highest reading.
C A_2 has the highest reading.
D A_3 has the highest reading. **[1]**

COMMAND WORD

identify: name/select/recognise.

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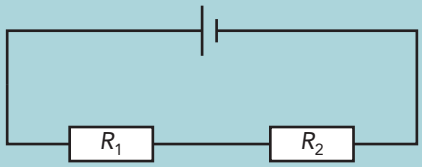
CONTINUED

2 Two resistors, R_1 and R_2, are connected in series. Resistor R_1 has double the resistance of resistor R_2.



Identify which *two* of the following statements about this circuit are correct.

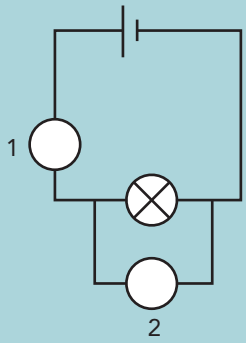
A The voltage across R_1 is twice that across R_2.

B The voltage across R_2 is twice that across R_1.

C The current is the same in both resistors.

D The current in R_1 is twice the current in R_2. **[2]**

3 Components 1 and 2 in this circuit are both measuring devices.



For each device, **state**:

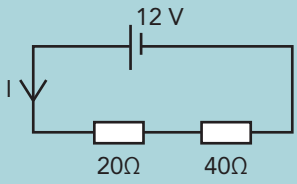
a the name of the device **[2]**

b the quantity it measures **[2]**

c the unit of its measurements. **[2]**

[Total: 6]

4 **Calculate** the current, I, flowing in this circuit.



[1]

COMMAND WORDS

state: express in clear terms.

calculate: work out from given facts, figures or information.

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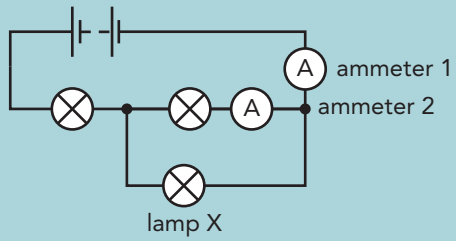
CONTINUED

5 The diagram shows three lamps and two ammeters in a circuit.



State what happens to each of the following if the filament in lamp X breaks and the lamp stops working.

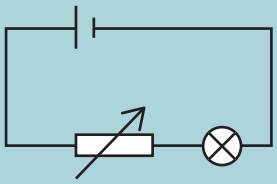
a the reading on ammeter 1 **[1]**

b the reading on ammeter 2 **[1]**

c the total resistance of the circuit **[1]**

[Total: 3]

6 A student uses this circuit to calculate the resistance of the lamp. She needs to add a voltmeter and an ammeter to the circuit.



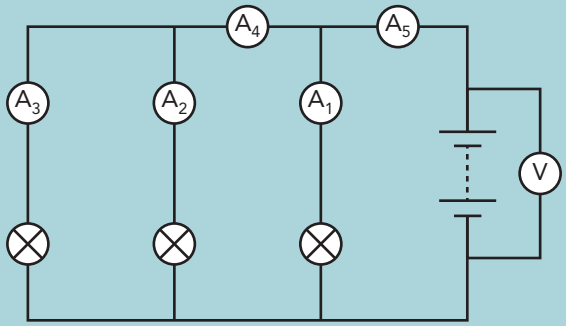
a Copy the diagram and add the voltmeter and ammeter to the circuit. **[2]**

b State what will happen to the brightness of the lamp if the student increases the resistance of the variable resistor. **[1]**

c She measures the current as 0.3 A when the p.d. across the lamp is 4 V. Use this information to calculate the resistance of the lamp. **[2]**

[Total: 5]

7 A circuit was set up as shown in the diagram.



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CONTINUED

a The table gives the current through three of the ammeters.

Complete the table by calculating the current through the other two ammeters. **[2]**

Ammeter	Reading on ammeter / A
A_1	0.7
A_2	1.2
A_3	0.7
A_4	
A_5	

b The filament in the middle lamp breaks.

Copy and complete the table by **deducing** the readings on the ammeters after this took place. **[3]**

Ammeter	Reading on ammeter / A
A_1	0.7
A_2	0.0
A_3	
A_4	
A_5	

[Total: 5]

8 Many circuits contain fuses. Figure P6.17 shows a cartridge fuse. A lamp is connected to the mains supply and takes a current of 6.2 A.

a State why a fuse is included in the circuit. **[1]**

b Identify which of these fuses should be used with the lamp.

A 3 A

B 5 A

C 7 A

D 13 A **[1]**

c **Explain** how a fuse works. **[2]**

d Explain why it is important to avoid touching a lamp or other electrical appliance with wet hands. **[1]**

[Total: 5]

COMMAND WORD

deduce: conclude from available information.

COMMAND WORD

explain: set out purposes or reasons/make the relationships between things clear/say why and/or how and support with relevant evidence.

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SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
draw and understand circuit diagrams	P6.01			
differentiate between series and parallel circuits	P6.01			
recall whether current varies around a series circuit	P6.01			
state the relative size of current through the source (for example, a cell or battery) and each branch of a parallel circuit	P6.01			
state the advantages of connecting lamps in parallel in a lighting circuit	P6.01			
recall and use the relationship between the sum of the p.ds across the components in a series circuit and the p.d. across the source (for example, a cell)	P6.02			
recall and use the relationship between the current from the source and the sum of the currents in the separate branches of a parallel circuit	P6.02			
state how the combined resistance of two resistors in parallel compares to the resistance of either resistor by itself	P6.02			
calculate the combined resistance of two or more resistors in series	P6.03			
calculate the effective resistance of two resistors in parallel	P6.03			
state what a fuse is used for and describe how it works	P6.04			
choose appropriate fuse ratings	P6.04			
state the hazards of using electrical appliances in damp conditions, when cables overheat or when insulation is damaged	P6.04			
state the hazards of using multi-plug adapters.	P6.04			

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P7

Electromagnetic effects

Only learners entered for Co-ordinated Supplement study this content

IN THIS CHAPTER YOU WILL:

- describe the magnetic fields around current-carrying conductors
- observe the force on a current-carrying conductor in a magnetic field
- describe the principle of an electric motor and list ways of increasing its strength
- describe the factors affecting the strength and direction of electromagnetic fields and forces
- describe the structure and operation of an electric motor
- list the factors affecting the size of an e.m.f. induced in a circuit
- explain how an a.c. generator works
- explain why electricity is transmitted at very high voltages
- describe the structure and use of step-up and step-down transformers.

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BEFORE YOU START

You have learnt about the electrical quantities we can measure or calculate. These include: current, potential difference, resistance, charge, energy, power and electromotive force.

For each quantity, write a definition, the letter used to represent the quantity in an equation (for example, l for length), and its unit.

Write down all the equations you know which involve these quantities.

In a small group, play a game to check your learning:

Create a set of cards. There should be one card for the name of each quantity, one card for the unit of each quantity, one card for time, and one card for seconds.

Place the cards face down in a pack. The first player turns two cards over. If they can connect the cards in a sentence or equation, they score a point.

Return the cards to the pack, mix them up, and then the next player takes their turn.

For example, if a player picks 'ohm' and 'current', they could say: 'when the resistance in ohms increases, the current drops'. If a student makes an incorrect link, other players can score a point by spotting the mistake and giving a correct answer.

SCIENCE IN CONTEXT P7.01

The magic of motors

Some things in science seem magical. For example, the fact that a plant can feed itself using sunlight is amazing. The electric motor is another example of the magic of science. As you will discover in this chapter, putting together an electric current and a magnetic field creates movement. This is the basis of all electric motors.

Electric motors have revolutionised our lives. It is easy to take them for granted, but anything you plug in which involves movement, contains a motor. Washing machines, hair dryers, electric vehicles, electric drills, and many more appliances which make our lives easier and better, use motors. Just think for a moment about how different your life would be without motors.

Motors have many medical applications. They are widely used in prosthetic limbs, and can pump fluids such as blood during dialysis. Surgeons can remotely control motorised devices to make surgery less invasive.

Figure P7.01 shows a girl with a prosthetic arm eating her dinner. Many prosthetic limbs have small motors inside them, greatly increasing their capabilities. Here, the motor allows the fingers to grip the French fries and apply the right amount of force to keep hold of them for her to then eat. Motors can be life changing and, in this case, replaces the movement lost to an amputee.

Figure P7.01: Small motors in prosthetic limbs allow a greater range of movement for people using them.

Discussion questions

1 List all the applications of motors you can think of. Discuss how the job each application performs would have been done before motors were invented.

2 Discuss whether you think there are any other scientific inventions or discoveries which have had as much impact as the electric motor.

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P7.01 Magnetic effect of current

In Chapter P5, we saw that an electromagnet can be made by passing a current through a coil of wire (a solenoid). Every electric current creates a magnetic field around it. An electromagnet uses this effect. Winding the wire into a coil is a way of concentrating the magnetic field. The flow of current results in a magnetic field around the solenoid. The field is similar to the field around a bar magnet (see Figure P7.02).

a

b

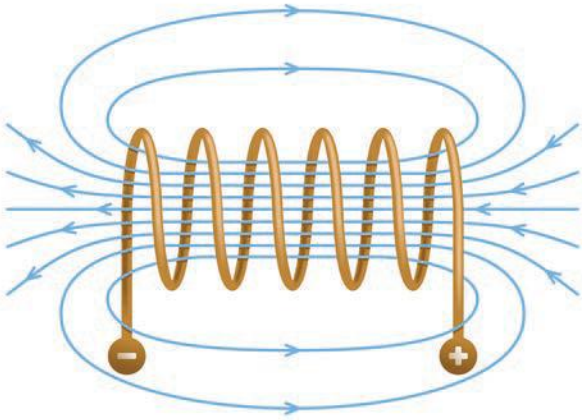

Figure P7.02 a: Current flowing through a coil around a soft iron core creates an electromagnet. **b:** The magnetic field around a solenoid.

The direction of the field lines can be determined by considering the direction of current at the ends of the coil. Imagine looking into one end of the coil. Is the current flow clockwise or anticlockwise? If it is clockwise that end will become a south pole, if it is anticlockwise it will become a north pole (Figure P7.03).

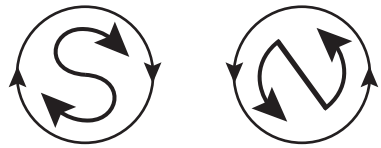

Figure P7.03: The outer circles represent the coil of the wire, and the arrows show the current. Notice that the arrows on the S and N match those for the current.

If you uncoil a solenoid, you will have a straight wire. With a current flowing through it, it will have a magnetic field around it as shown in Figure P7.04. The field lines are circles around the current.

The **right-hand grip rule** tells you the direction of the field lines around a straight wire. Imagine gripping the wire with your right hand so that your thumb points in the direction of the current. The curve of your fingers shows the shape and direction of the field lines.

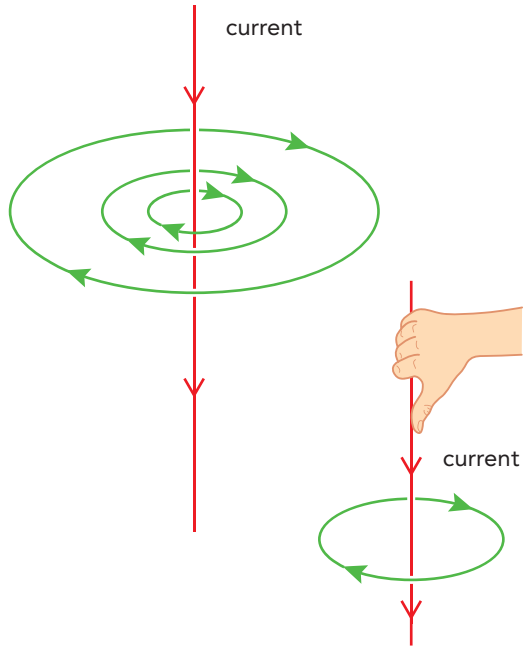

Figure P7.04: Magnetic field around a wire.

KEY WORDS

right-hand grip rule: a rule which gives the direction of field lines around a straight wire when a current flows through it.

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Comparing the strength and direction of magnetic fields

Current in a wire

Further from the wire, the circular field lines are further apart, showing that the field is weaker. If the current is greater, the field will be stronger and so the lines will be closer together.

The direction of the field lines is reversed when the current is reversed.

Current in a solenoid

The field lines are close together at the poles of the electromagnet. Further from the coil, the lines are further apart (illustrating a weaker field). Inside the coil the field lines run parallel to each other showing that the field is uniform (its strength is constant). Again, increasing the current gives a stronger field.

When the current is reversed, the field direction is also reversed.

Questions

P7.01 Copy and complete these sentences.

There is a magnetic field around a conductor when it carries _____.

The field lines around a straight wire are _____.

The direction of these field lines can be found using the _____ _____ _____ rule.

The field around a solenoid is the same as that around a _____ _____.

P7.02 What must be added to a solenoid to make it into an electromagnet?

P7.03 A current flows downwards in a wire that passes vertically through a small hole in a table top. Will the magnetic field lines around it go clockwise or anticlockwise, as seen from above?

P7.02 Force on a current-carrying conductor

The idea of an electric motor is this. There is a magnetic field around an electric current. This magnetic field can be attracted or repelled by another magnetic field to produce movement. This is called the **motor effect**.

An electric motor has a coil with a current flowing around it (an electromagnet) in a magnetic field. It turns because the two magnetic fields interact with each other. However, it is not essential to have a coil to produce movement. The basic requirements are:

- a magnetic field
- a current flowing which cuts across the magnetic field lines.

When a current is passed through the aluminium foil shown in Figure P7.05 it has a magnetic field around it. This interacts with the field of the strong, permanent magnet, creating a force. The foil has been pushed downwards by this force.

The direction of the force can be reversed by:

- reversing the direction of the current
- reversing the direction of the field of the permanent magnet by turning it round.

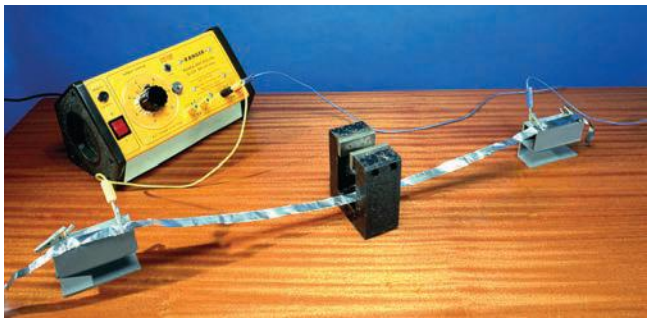

Figure P7.05: The motor effect. This can be summarised as current + magnetic field = movement.

KEY WORDS

motor effect: when current flows in a wire in a magnetic field which is not parallel to the current, a force is exerted on the wire.

Fleming's left-hand rule

Figure P7.06a uses arrows to represent three important quantities in the demonstration in Figure P7.05:

- the magnetic field of the permanent magnet
- the current
- the force which moves the aluminium strip.

The magnetic field is horizontal between the poles. The current is also horizontal, but at right angles to the field. The force is vertical, so the foil moves down. The three quantities are all at right angles to each other (Figure P7.06a). To remember how they are arranged,

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physicists use **Fleming's left-hand rule** (Figure P7.06b). This states that if the thumb and first two fingers of the left hand are extended at right angles to each other, and the first finger points in the direction of the field, and the second finger in the direction of current, then the thumb will indicate the direction of the force.

KEY WORDS

Fleming's left-hand rule: a rule that gives the relationship between the directions of force, field and current when a current flows across a magnetic field.

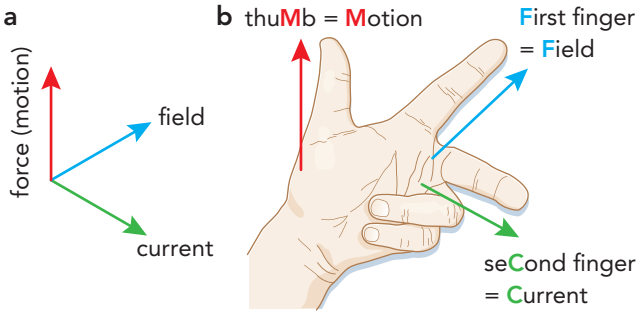

Figure P7.06 a: Force, field and current are at right angles to each other. **b:** Fleming's left-hand rule.

It is worth practising holding your thumb and first two fingers at right angles like this. It takes time to get this right. Then learn what each finger represents:

- the First finger is Field
- the seCond finger is Current
- the thuMb is force or Motion.

We use Fleming's left-hand rule to predict the direction of the force on a current-carrying conductor in a magnetic field. By keeping your thumb and fingers at right angles to each other, you can show that reversing the direction of the current or field reverses the direction of the force. (Do not try changing the direction of individual fingers. You have to twist your whole hand around at the wrist.)

P7.03 The d.c. motor

The movement created in the motor effect experiments is not very useful. The conductor moves out of the field and the effect is over.

A motor is designed to use the motor effect to create a turning movement. Figure P7.07b shows that inside a motor there are magnets and coils of wire. These are arranged to create the turning movement.

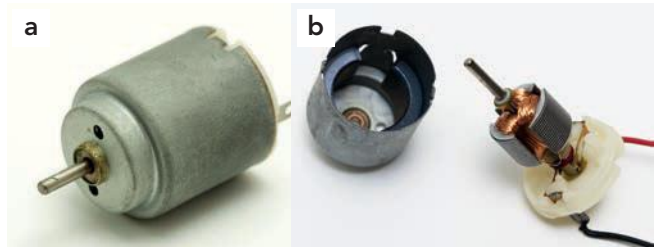

Figure P7.07 a: The type of motor used in school laboratories. **b:** The motor taken apart. Notice the copper coils and the curved magnets inside the casing and the coil.

The turning movement happens because the wire is coiled. Look at the coil in Figure P7.08. The current flows up the right-hand side of the coil and down the left. This means that the forces on the two wires are in opposite directions. The right-hand wire moves up and the left-hand wire moves down. This makes the coil spin. The brushes and **commutator** make sure that the current always flows the same way round the coil, in this case, anticlockwise.

KEY WORD

commutator: a device used to allow current to flow to and from the coil of a d.c. motor or generator.

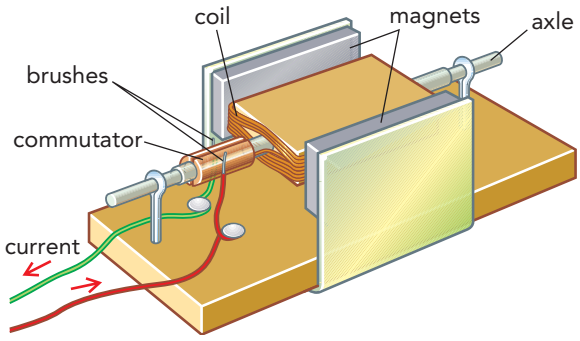

Figure P7.08: This model is used to show the principles of operation of an electric motor.

For a d.c. motor like this (Figure P7.08) to be of any use, its axle must be connected to something that is to be turned – a wheel, a pulley or a pump, for example. This model motor is not very powerful. The turning effect can be increased by:

- increasing the number of turns of wire in the coil
- increasing the current
- increasing the strength of the magnetic field.

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Electric motors explained

We can apply Fleming's left-hand rule to an electric motor. Figure P7.09a shows a simple electric motor with its coil horizontal in a horizontal magnetic field. The coil is rectangular. What forces act on each of its four sides?

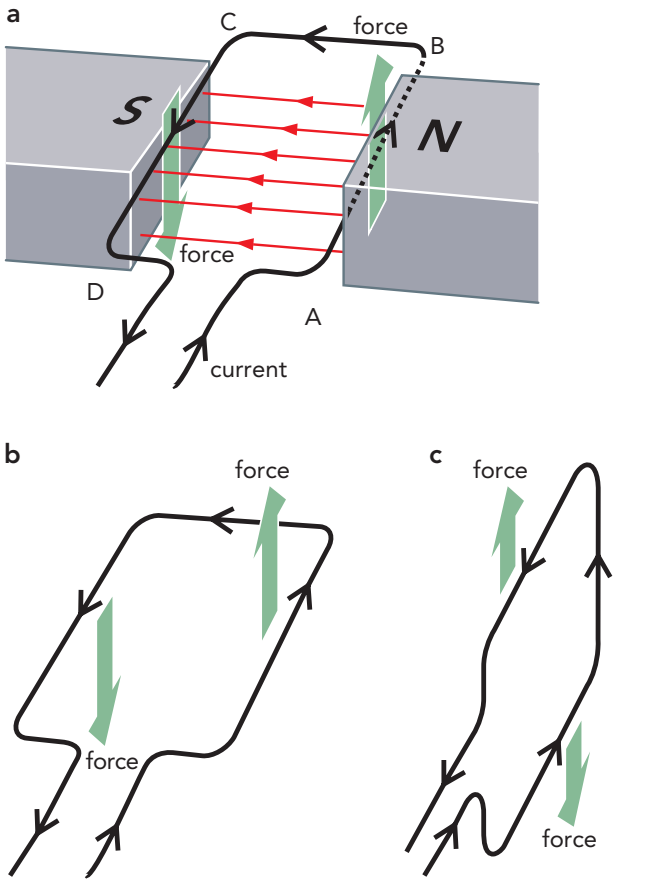

Figure P7.09 a: A simple electric motor. Only the two longer sides experience a force, since their currents cut across the magnetic field. **b:** The two forces provide the turning effect needed to make the coil rotate. **c:** When the coil is in the vertical position, the forces have no turning effect.

- Side AB: the current flows from A to B, across the magnetic field. Fleming's left-hand rule shows that a force acts on it, vertically upwards.
- Side CD: the current is flowing in the opposite direction to the current in AB, so the force on CD is in the opposite direction, downwards.
- Sides BC and DA: the current here is parallel to the field. Since it does not cross the field, there is no force on these sides.

Figure P7.09b shows a simplified view of the coil. The two forces acting on it are shown. They cause the coil to turn anticlockwise. The two forces provide a turning effect which causes the motor to spin. From Figure P7.09c, you can see that the forces will not turn the coil when it is vertical. This is where we have to rely on the coil's momentum to carry it further round.

Keeping the motor turning

As the momentum of the coil carries it round, the wires AB and CD swap positions. The commutator spins with the coil. The brushes do not move. This means that, in the motor in Figure P7.10, current always flows in on the right, and anticlockwise round the coil. This means that the motor keeps turning in the same direction.

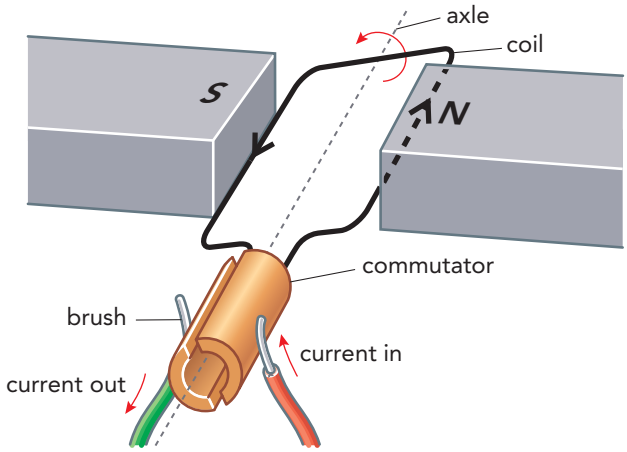

Figure P7.10: A spinning electric motor. Every half turn the commutator reverses the connections to the power supply, so that the motor keeps turning in the same direction.

The diagrams show the coil as if it were a single turn of wire. In practice, the coil might have hundreds of turns of wire, resulting in forces hundreds of times as great. A coil causes the current to flow across the magnetic field many times, and each time it feels a force. A coil is simply a way of multiplying the effect that would be experienced using a single length of wire.

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Questions

P7.04 Describe the energy transfers that happen in an electric motor.

P7.05 A student does an experiment to show the motor effect using the apparatus shown in Figure P7.11. The wire moves upwards.

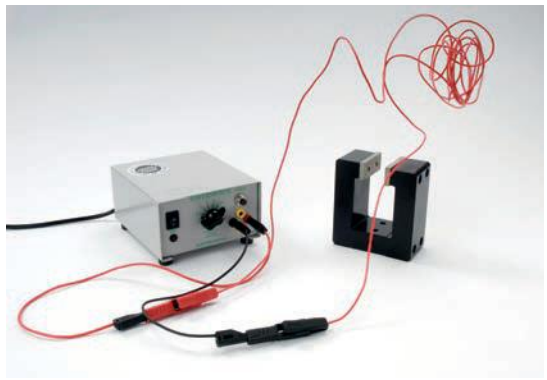

Figure P7.11: Apparatus for an experiment to show the motor effect.

a Describe *two* ways in which the student could reverse the effect to make the wire move downwards.

b The student moves the wire so that it passes from the north to the south pole of the magnet as shown in Figure P7.12. Explain why the wire does not move.

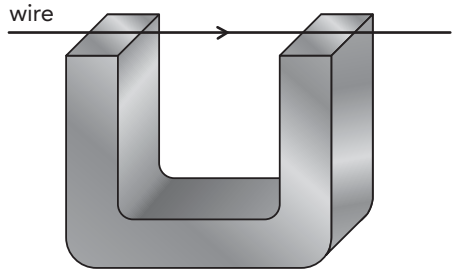

Figure P7.12: The wire passes from the north to the south pole of the magnet.

P7.06 For Fleming's left-hand rule, write down the three quantities that are at 90° to each other. Next to each one, write down the finger that represents it.

P7.07 In Figure P7.13, crosses represent a magnetic field into the page and dots represent a field coming out of the page. In each case, use Fleming's left-hand rule to determine the direction of the force on the wire.

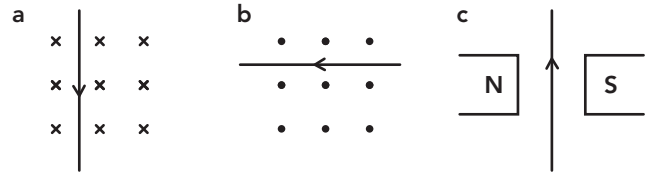

Figure P7.13: The crosses represent a magnetic field into the page and dots represent a field coming out of the page.

P7.04 Electromagnetic induction

A motor is a device that transfers energy by an electrical current into a mechanical (kinetic) energy store. An electrical generator does the opposite. It transfers energy from a mechanical energy store by an electrical current. An electric motor can be used in reverse to generate electricity. If you connect an electric motor to a lamp and spin its axle, the lamp will light, showing that you have generated a voltage which causes a current to flow through the lamp (Figure P7.14).

Inside the motor, the coil is spinning around in the magnetic field provided by the permanent magnets. The result is that a current flows in the coil, and this is shown by the lamp. We say that the current has been induced, and the motor is acting as a generator.

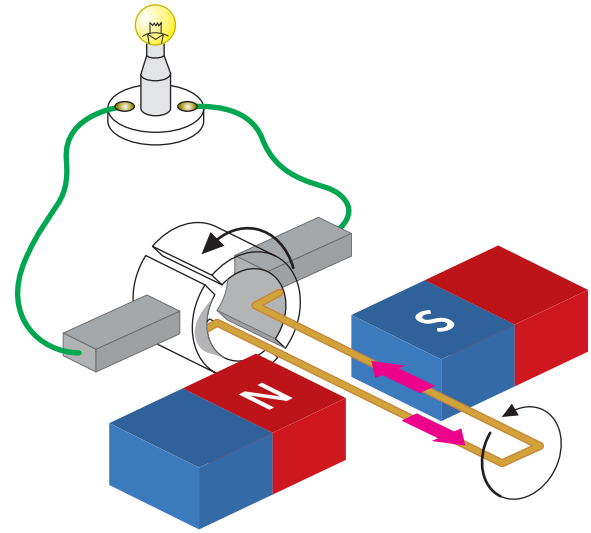

Figure P7.14: A motor can act as a generator. Spin the motor and the lamp lights, showing that an induced current flows around the circuit.

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All generators have three things in common:

- a magnetic field (provided by magnets or electromagnets)
- a coil of wire (fixed or moving)
- movement (the coil and magnetic field move relative to one another).

When the coil and the magnetic field move relative to each other, a current flows in the coil if it is part of a complete circuit. This is known as an induced current. If the generator is not connected up to a circuit, there will be an **induced e.m.f. (or induced voltage)** across its ends, ready to make a current flow around a circuit.

KEY WORDS

induced e.m.f. (or induced voltage): the e.m.f. created in a conductor when it cuts through magnetic field lines.

The principles of electromagnetic induction

The process of generating electricity from motion is called **electromagnetic induction**.

As we have seen, a coil of wire and a magnet moving relative to each other are needed to induce a voltage across the ends of a wire. If the coil is part of a complete circuit, the induced e.m.f. will make an induced current flow around the circuit.

KEY WORDS

electromagnetic induction: the production of an e.m.f. across an electrical conductor when there is relative movement between the conductor and a magnetic field.

In fact, you do not need to use a coil. A single wire is enough to induce an e.m.f., as shown in Figure P7.15a. The wire is connected to a sensitive meter to show when a current is flowing.

- Move the wire down between the poles of the magnet and a current flows.
- Move the wire back upwards and a current flows in the opposite direction.
- Alternatively, the wire can be kept stationary and the magnet moved up and down. Again, a current will flow.

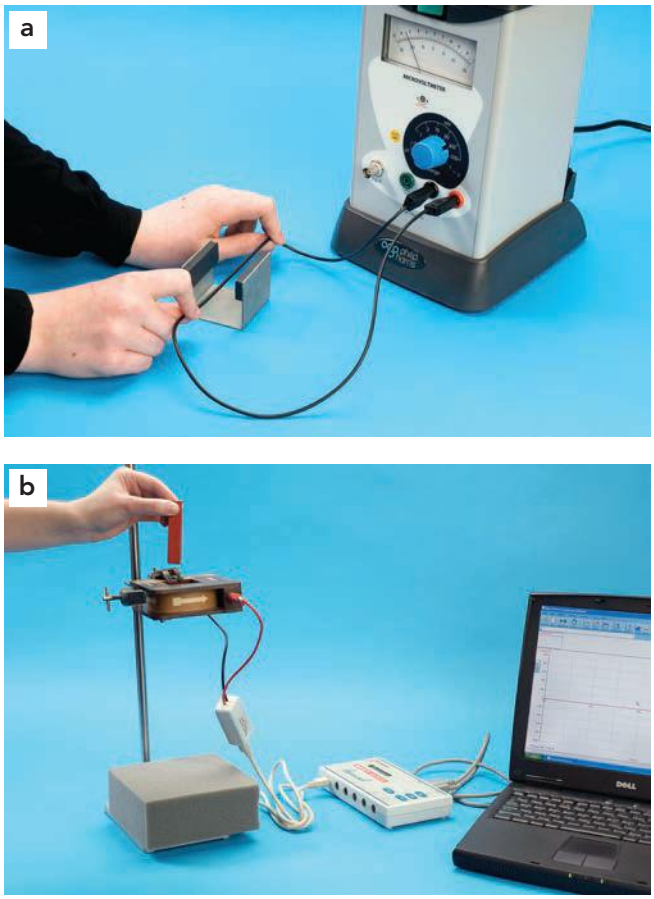

Figure P7.15 a: Move a wire up and down between the poles of a stationary magnet and an induced current will flow. **b:** Similarly, move a magnet into and out of a coil of wire and an induced current will again flow.

You can see similar effects using a magnet and a coil (Figure P7.15b). Pushing the magnet into and out of the coil induces a current, which flows back and forth in the coil. Here are two further observations:

- Reverse the magnet to use the opposite pole and the current flows in the opposite direction.
- Hold the magnet stationary next to the wire or coil and no current flows. They must move relative to each other, or nothing will happen.

In these experiments it helps to use a centre-zero meter. Then, when the needle moves to the left, it shows that the current is flowing one way; when it moves to the right, the current is flowing the other way.

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Increasing the induced e.m.f.

There are three ways to increase the e.m.f. induced in a coil or wire:

- use a stronger magnet
- move the wire or coil more quickly relative to the magnet
- use a coil with more turns of wire; each turn of wire will have an e.m.f. induced in it, and these all add together to give a bigger e.m.f.

Questions

P7.08 Copy and complete these sentences.

An e.m.f. is induced in a conductor in a magnetic field if either the _____ or the _____ moves relative to the other.

The size of the e.m.f. induced in a coil can be increased by increasing _____, _____ or _____.

The direction of the e.m.f. can be _____ by reversing the field or the direction of movement.

P7.09 Which of the following would not induce a current?

A moving a wire between the poles of a magnet

B taking a bar magnet out of a coil or wire

C holding a wire between the poles of a magnet

D spinning a coil or wire in a magnetic field

P7.10 A student holds a piece of copper wire which is connected to an ammeter between the poles of a magnet, but he does not get a reading on the ammeter. What should he do to make a current flow?

P7.11 A student moves a bar magnet into a coil of wire and a current flows. Describe *two* changes which would make the current flow in the opposite direction.

P7.12 An a.c. generator and a cell can both be used to light a bulb. Describe how the current flowing through the bulb is different in each case.

Induction and field lines

We can understand electromagnetic induction by thinking about magnetic field lines. Figure P7.16 shows the field lines between the poles of a horseshoe magnet. As the wire is moved down between the poles of the magnet, it cuts the field lines of the magnet. Cutting the field lines induces the current.

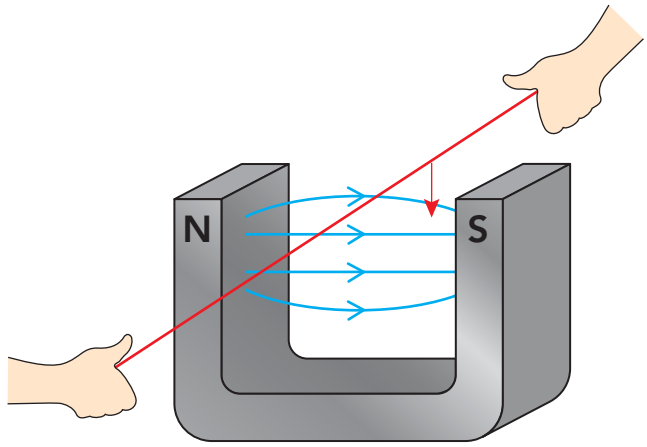

Figure P7.16: As the wire cuts through the field lines, an e.m.f. is induced in it. If the wire is part of a complete circuit, a current will flow.

This idea helps us to understand the factors that affect the magnitude and direction of the induced e.m.f.

- When the magnet is stationary, there is no cutting of field lines and so no e.m.f. is induced.
- When the magnet is further from the wire, the field lines are further apart and so fewer are cut, giving a smaller e.m.f.
- When the magnet is moved quickly, the lines are cut more quickly and a bigger e.m.f. is induced.
- A coil gives a bigger effect than a single wire, because each turn of wire cuts the magnetic field lines. This means that each contributes to the induced e.m.f.

P7.05 The a.c. generator

The discovery of electromagnetic induction led to the development of the electricity supply industry. In particular, it allowed engineers to design generators that could supply electricity. At first, this was only done on a small scale, but gradually generators got bigger and bigger, until, like the ones shown in Figure P7.17, they were capable of supplying the electricity demands of thousands of homes.

A generator of this type produces alternating current (a.c.). Alternating current flows first one way then the other as the coils turn in the magnetic field.

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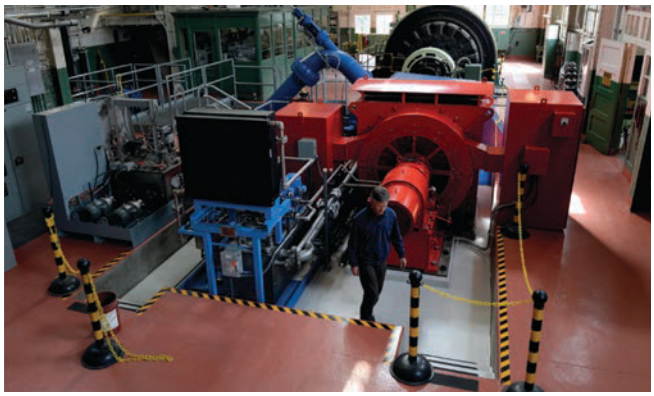

Figure P7.17: The turbine and generator in the generating hall of a nuclear power station. The turbines are fed by high-pressure steam in pipes.

Figure P7.18 shows a simple **a.c. generator**, which produces alternating current. In principle, an a.c. generator is like a d.c. motor, working in reverse. The axle is made to turn so that the coil spins around in the magnetic field, and a current is induced. The other difference is in the way the coil is connected to the circuit beyond. A d.c. motor uses a split-ring commutator, whereas an a.c. generator uses slip rings. The **slip rings** rotate with the coil. The brushes rub against the slip rings and so have the same e.m.f. as the sides of the coil.

KEY WORDS

a.c. generator: a device such as a dynamo used to generate alternating current.

slip rings: a device used to allow current to flow to and from the coil of an a.c. generator.

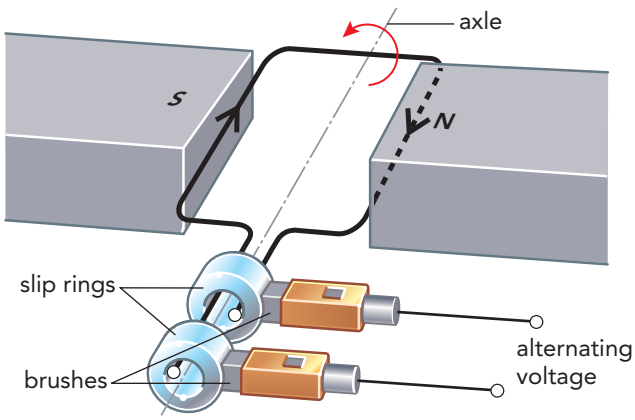

Figure P7.18: A simple a.c. generator works like a motor in reverse. The slip rings and brushes are used to connect the alternating current to the external circuit.

Why does this generator produce alternating current? As the coil rotates, each side of the coil passes first the magnetic north pole and then the south pole.

Figure P7.19 shows a graph of this. When the coil is horizontal, it cuts through the field lines inducing a voltage. As it turns to vertical, it cuts fewer field lines so the voltage decreases to zero. As it continues back to horizontal it cuts through the field lines in the opposite direction, giving a peak voltage in the opposite direction.

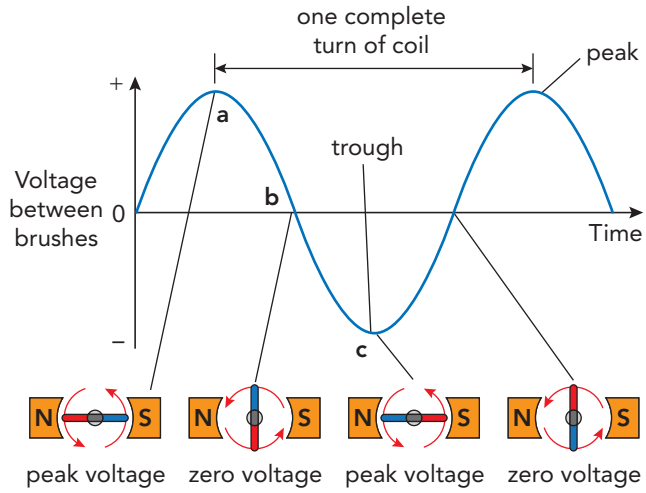

Figure P7.19: A graph to represent an alternating voltage. As the coil turns, the voltage reaches a peak in one direction, decreases to zero, then reverses.

This means that the induced current flows first one way, and then the other. In other words, the current in the coil is alternating.

The current flows out through the slip rings. Each ring is connected to one end of the coil, so the alternating current flows out through the brushes, which press against the rings.

There are four ways of increasing the voltage generated by an a.c. generator like the one shown in Figure P7.18:

- turn the coil more rapidly
- use a coil with more turns of wire
- use a coil with a bigger area
- use stronger magnets.

Each of these changes increases the rate at which magnetic field lines are cut, and so the induced e.m.f. is greater. For the a.c. generator shown in Figure P7.18, each revolution of the coil generates one cycle of alternating current. Spin the coil 50 times each second and the a.c. generated has a frequency of 50 Hz.

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Figure P7.19 shows how the e.m.f. produced by an a.c. generator varies as the coil turns. If we think about how the coil cuts through magnetic field lines, we can understand why the a.c. graph varies between positive and negative values. With the coil in the horizontal position, as shown in position **a**, its two long sides are cutting rapidly through the magnetic field lines. This gives a large induced e.m.f., corresponding to a peak in the a.c. graph. When the coil is vertical (position **b**), its long sides are moving along the field lines, so they are not cutting them. This gives no induced e.m.f., a zero point on the a.c. graph. When the coil has turned through 180° to position **c**, it will be cutting field lines quickly again, but in the opposite direction, so the induced e.m.f. will again be large, but this time it will be negative – this corresponds to a trough on the graph.

ACTIVITY P7.01

Generating fitness

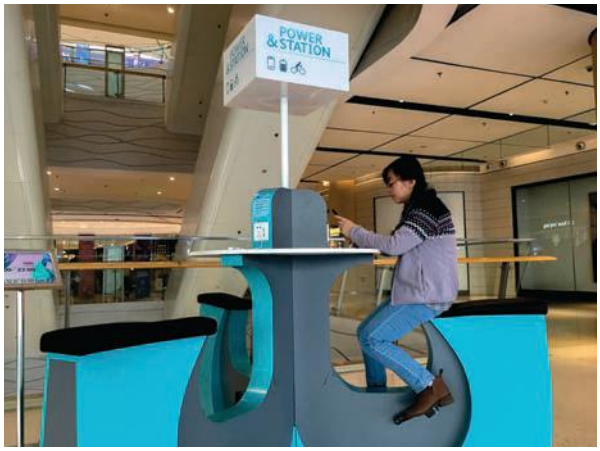

Figure P7.20: Using an exercise bike to charge a mobile phone.

The woman in Figure P7.20 is charging her mobile phone. As she pedals the exercise bike, she turns a generator to induce a current which is used to charge her phone.

Produce a poster to attract customers to use a bike charger in a public place. You should include information about how the system helps to:

- save money
- improve the user's health
- protect the environment.

You should also include a more detailed section for the user to read as they pedal. This should explain how the system works and advise the customer how to charge their phone as quickly as possible.

CONTINUED

Peer assessment

Swap posters with another student. Rate their poster using the following table. Comment on what works well, and what would make it even better.

	Excellent / good / adequate / needs improvement	Comments
Presentation – colour, layout, and so on		
Explains health and environmental benefits		
Clearly explains how the device works		
Suggests ways to increase charging rate		

P7.06 The transformer

Generators in power stations generate electricity. Power stations may be 100 km or more from the places where the electricity they generate is used. This electricity must be distributed around the country (Figure P7.21).

Figure P7.21: Electricity is usually generated at a distance from where it is used. If you look on a map, you may be able to trace the power lines that bring electrical power to your neighbourhood.

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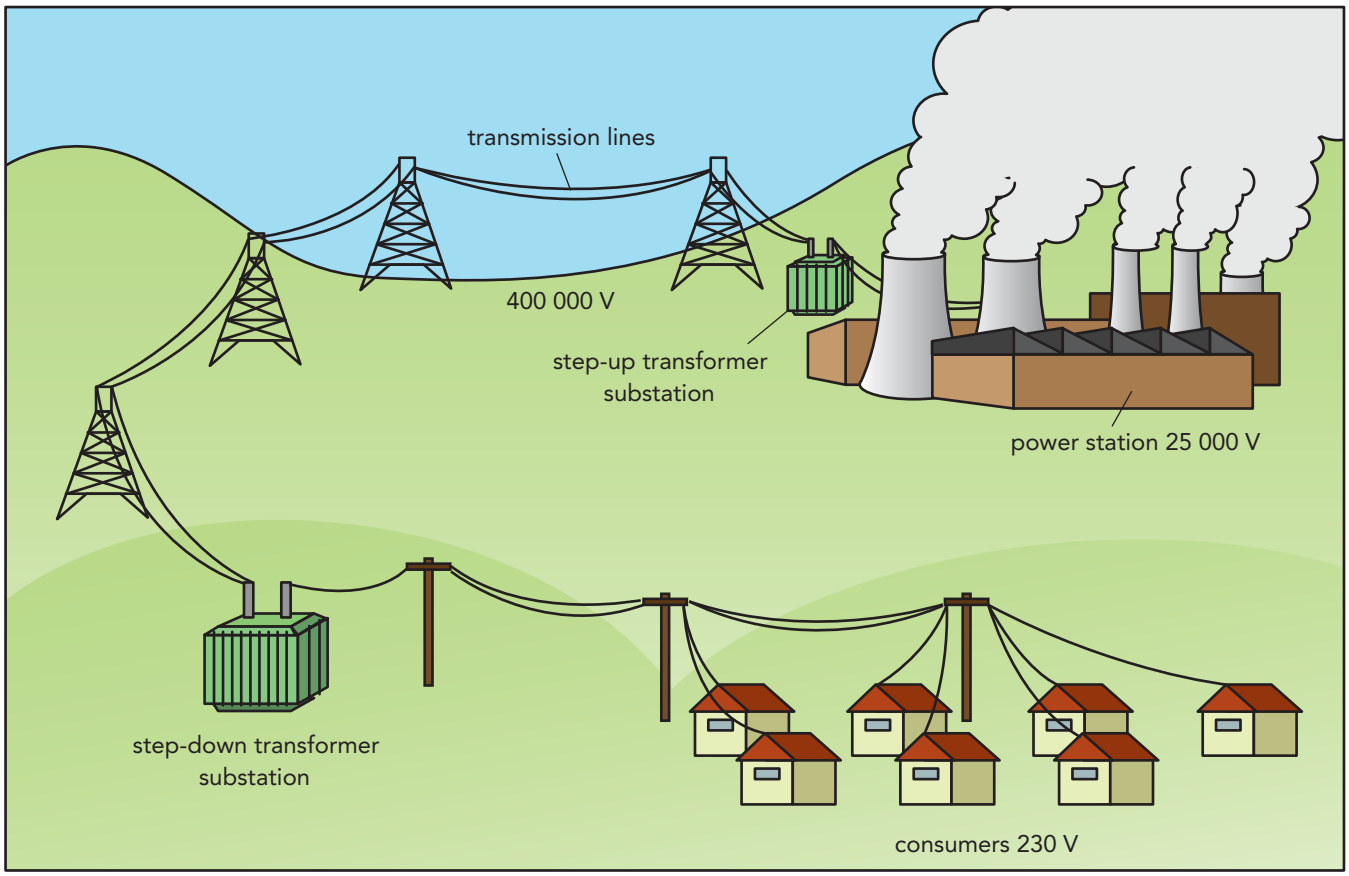

Figure P7.22: In a national grid, voltages are increased to reduce energy losses, then reduced to a relatively safe level.

High-voltage electricity leaves the power station. Its voltage may be as high as 1 million volts. To avoid danger to people, it is usually carried in cables called **power lines** slung high above the ground between tall pylons. Lines of pylons carry wires across the countryside, heading for the urban and industrial areas that need the power (Figure P7.22). This is a country's **national grid**.

KEY WORDS

power line: cable used to carry electricity from power stations to consumers.

national grid: the system of power lines, pylons and transformers used to carry electricity around a country.

When the power lines approach the area where the power is to be used, they enter a local distribution centre. Here the voltage is reduced to a less hazardous level, and the power is sent through more cables (overhead or underground) to local substations. In the substation, the voltage is reduced to the local supply voltage, typically 230 V. Wherever you live, there is likely to be a substation in the neighbourhood. It may be in a securely locked building, or the electrical equipment may be surrounded by fencing, which carries notices warning of the hazard (Figure P7.23).

Figure P7.23: An electricity substation has warning signs like this to indicate the extreme hazard of entering the substation.

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From the substation, electricity is distributed to houses, shops, etc. In some countries, the power is carried in cables buried underground. Other countries use tall poles and overhead wires.

Why use high voltages?

The high voltages used to transmit electrical power around a country are dangerous. That is why the cables that carry the power are supported high above people, traffic and buildings on tall pylons. Sometimes the cables are buried underground, but this is much more expensive, and the cables must be safely insulated. The reason for using high voltages is to reduce the loss of energy due to the cables heating up. This heating happens much more when the same power is transmitted at a lower voltage.

The structure of a transformer

A **transformer** is a device used to increase or decrease the voltage of an electricity supply.

Power stations typically generate electricity at 25 kV. This has to be converted to the grid voltage (typically 400 kV) using transformers. This is known as stepping up the voltage.

Figure P7.24a shows the construction of a suitable transformer. Every transformer has three parts:

- A **primary coil**: the incoming voltage V_p is connected across this coil.
- A **secondary coil**: this provides the voltage V_s to the external circuit.
- An iron core: this links the two coils.

Notice that there is no electrical connection between the two coils. They are linked together only by the soft iron core. The wires are insulated so no current flows from one coil to the other. Notice also that the voltages are both alternating voltages. Transformers only work with a.c. All they do is change the size of an a.c. voltage.

The power station transformer described earlier steps up the voltage from 25 kV to 400 kV – it is increased by a factor of 16. To step up the voltage by a factor of 16, there must be 16 times as many turns on the secondary coil as on the primary coil. By comparing the numbers of turns on the two coils we can tell how the voltage will be changed.

- A **step-up transformer** increases the voltage. There are more turns on the secondary coil than on the primary coil.
- A **step-down transformer** reduces the voltage. There are fewer turns on the secondary coil than on the primary coil.

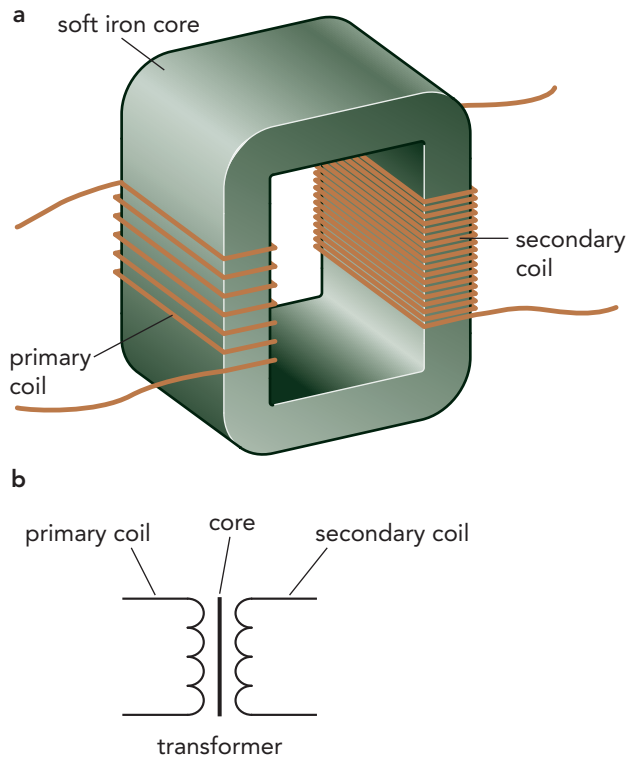

Figure P7.24 a: The structure of a transformer. This is a step-up transformer because there are more turns on the secondary coil than on the primary. If the connections to it were reversed, it would be a step-down transformer. **b:** The circuit symbol for a transformer shows the two coils with the core between them.

KEY WORDS

transformer: a device used to change voltage of an a.c. electricity supply.

primary coil: the input coil of a transformer.

secondary coil: the output coil of a transformer.

step-up transformer: a transformer which increases the voltage of an a.c. supply.

step-down transformer: a transformer which decreases the voltage of an a.c. supply.

Note that, when the voltage is stepped up, the current is stepped down, and when the voltage is stepped down, the current is stepped up.

The ratio of the number of turns tells us the factor by which the voltage will be changed. We can write an equation, known as the transformer equation, relating the two voltages, V_p and V_s, to the numbers of turns on each coil, N_p and N_s:

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KEY EQUATION

$$\frac{\text{voltage across primary coil}}{\text{voltage across secondary coil}} = \frac{\text{number of turns on primary}}{\text{number of turns on secondary}}$$

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

WORKED EXAMPLE P7.01

There are very large transformers between power stations and the transmission cables.

One of these transformers has 800 turns on its primary coil and 16 000 turns on its secondary coil. The voltage across its primary coil is 25 kV.

a State what type of transformer this is.

b Calculate the voltage across its secondary coil.

Step 1: Write down what you know: The transformer has more turns on the secondary coil than the primary so it is a step-up transformer. This means the voltage should increase. Use this to check your answer to the next part.

Step 2: Draw a simple transformer as shown in Figure P7.25. Mark on it the information given in the question.

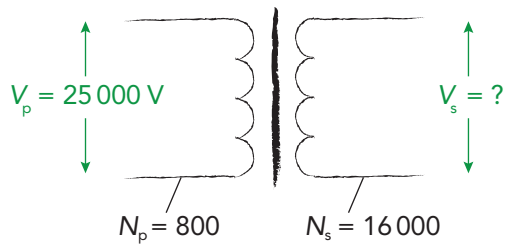

Figure P7.25: Transformer symbol with the quantities given in the question.

Step 3: Write down the transformer equation.

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

Step 4: Substitute in the values from the question.

$$\frac{25000\ \text{V}}{V_s} = \frac{800}{16000}$$

CONTINUED

Step 5: Rearrange the equation to find V_s.

$$V_s = \frac{25000\ \text{V} \times 16000}{800}$$
$$= 500000\ \text{V}$$

Check that this is greater than the primary voltage, as expected.

Answer

a step-up transformer

b $V_s = 500\,000$ V

It is often useful to do a quick mental calculation first. For example, if a transformer decreases voltage from 230 V to 60 V, it has reduced it by about a quarter. This means the number of turns on the secondary coil must be roughly a quarter of the number of turns on the primary coil. This is an approximate calculation. It helps you check whether your final answer is sensible.

Questions

P7.13 **a** Copy and complete these sentences.

Electricity is distributed by the national _____. This consists of substations, cables and _____.

The electricity is transmitted at very high _____ to _____ energy being lost as heat in the cables.

The voltage can be increased or decreased by _____.

b Figure P7.26 shows a transformer.

Name the parts labelled A, B and C.

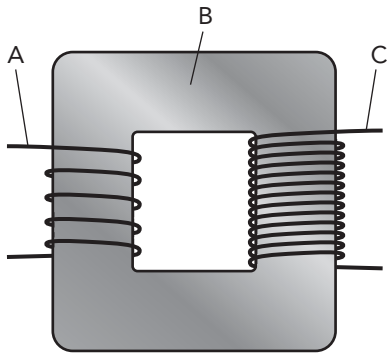

Figure P7.26: A transformer.

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c Explain whether this is a step-up or step-down transformer.

P7.14 A transformer has ten turns on the primary coil and five turns on the secondary. A voltage of 12 V is applied across the primary coil.

a Is this a step-up or step-down transformer?

b Use the transformer equation to calculate the output voltage of the transformer.

P7.15 Copy and complete Table P7.01. Calculate the missing information using the transformer equation.

N_p	N_s	V_p	V_s	Step-up or step-down transformer?
10	20		12	step-up
10		1.2	12	
	50	240	6	
10000	20	115000		

Table P7.01: Transformer calculations.

P7.16 A portable radio has a built-in transformer so that it can work from the mains instead of batteries. Is this a step-up or step-down transformer?

P7.17 A transformer increases the 1100 V from a power station to 132000 V for transmission. Calculate the number of turns on the primary coil when the secondary coil has 6000 turns.

REFLECTION

In these calculations it is useful to think about whether the answer is sensible. Which of the following suggestions are helpful for you? What does this tell you about how you work?

- Draw the transformer and write the numbers on it.
- Draw a diagram of the situation.
- Do a quick approximate calculation first.
- Decide whether the transformer is step-up or step-down, and what this tells you about your answer.

Think about whether you can apply any of these ideas when you do other calculations.

Calculating current

To transmit a certain power, P, we can use a small current, I, if we transmit the power at high voltage, V. This follows from the equation for electrical power:

$$\text{electrical power } P = IV$$

Worked example P7.02 shows how this works.

WORKED EXAMPLE P7.02

An electrical heater has a power rating of 2000 W. Calculate the current required if the voltage is:

a 230 V

b 12 V

Step 1: Write down what you know and what you need to find:

$P = 2000\,\text{W}$

$V = 230\,\text{V}$

$I = ?$

Step 2: Write down the equation you will use and put in the values you know

$I = P \div V = 2000 \div 230$

Step 3: Calculate the answer:

$I = 8.7\,\text{A}$

Repeat for the 12 V supply

$I = P \div V$

$= 2000 \div 12$

$= 166.7\,\text{A}$

It is clear that the smaller voltage means a much bigger current.

Energy saving

There is a good reason for using high voltages. It means that the current flowing in the cables is relatively low, and this wastes less energy. This can be explained as follows.

A consumer needs a certain amount of power. This power can be delivered as:

- high voltage, low current or
- low voltage, high current.

Calculating power losses

When a current flows in a wire or cable, some of the energy it is carrying is lost because of the cable's resistance – the cables get warm. A small current wastes less energy than a high current.

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We can calculate the rate of energy loss in the cables, or the power loss, by putting together two equations we met in Chapter P5:

$$\text{power} = \text{current} \times \text{potential difference}$$

$$P = IV$$

and

$$\text{potential difference} = \text{current} \times \text{resistance}$$

$$V = IR$$

$P = IV$ becomes $P = I(IR)$ or $P = I^2R$.

KEY EQUATION

power loss = square of current in the cable × resistance

$$P = I^2R$$

Electrical engineers do everything they can to reduce the energy losses in the cables. If they can reduce the current to half its value (by doubling the voltage), the losses will be one-quarter of their previous value. This is because power losses in cables are proportional to the square of the current flowing in the cables:

- Double the current gives four times the losses.
- Three times the current gives nine times the losses.

WORKED EXAMPLE P7.03

A 20 kW generator gives an output of 5 kV. This is transmitted to a workshop by cables with a resistance of 20 Ω. Calculate:

a the power loss in the cables

b the effect of using a transformer to increase the output voltage to 20 kV assuming that the power output remains the same.

When answering this question, it is important to realise there are two different powers involved: the power of the generator and the power loss in the cables.

Step 1: Calculate the current in the wires at 5 kV using the equation:

generator power, $P = IV$

Rearrange the equation and substitute values:

$I = P \div V = 20\,000\,\text{W} \div 5000\,\text{V} = 4\,\text{A}$

Step 2: Calculate the power loss:

$P = I^2R = (4\,\text{A})^2 \times 20\,\Omega = 320\,\text{W}$

(this is the answer to part **a**).

CONTINUED

Step 3: Calculate the current in the wires at 20 kV:

$P = IV$

$I = P \div V = 20\,000\,\text{W} \div 20\,000\,\text{V} = 1\,\text{A}$

Step 4: Calculate the power loss:

$P = I^2R = (1\,\text{A})^2 \times 20\,\Omega = 20\,\text{W}$

Answer

a 320 W

b Using the transformer to decrease the voltage greatly reduces the power loss, from 320 W to 20 W.

From the results of Worked example P7.03, you can see why electricity is transmitted at high voltages. The higher the voltage, the smaller the current in the cables, and so the smaller the energy losses. Increasing the voltage by a factor of four reduces the current by a factor of four. This means that the power lost in the cables is greatly reduced (in fact, it is reduced by a factor of 4^2, which is 16), and so thinner cables can safely be used.

The current flowing in the cables is a flow of coulombs of charge. At high voltage, we have fewer coulombs flowing, but each coulomb carries more energy with it.

Thinking about power

If a transformer is 100% efficient, no power is lost in its coils or core. This is a reasonable approximation, because well-designed transformers waste only about 0.1% of the power transferred through them. This allows us to write an equation linking the primary and secondary voltage, V_p and V_s, to the primary and secondary currents, I_p and I_s, using $P = IV$.

KEY EQUATION

power into primary coil = power out of secondary coil

$$I_p \times V_p = I_s \times V_s$$

It is important to remember that this equation assumes that no power is lost in the transformer. Worked example P7.04 shows how to use this equation.

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WORKED EXAMPLE P7.04

A school power pack has an output voltage of 9 V. It is plugged in to the 230 V mains supply. The power pack contains a transformer. The output current of the power pack is 3 A. Calculate the current supplied to the primary coil of the transformer in the power pack. Assume there are no energy losses in the transformer.

Step 1: Draw a transformer symbol and mark on the information from the question (Figure P7.27):

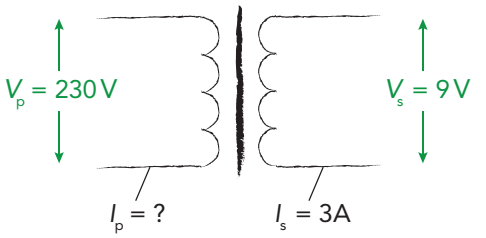

Figure P7.27: Transformer symbol with the known quantities.

Step 2: Write down the transformer power equation.

$$I_p \times V_p = I_s \times V_s$$

Step 3: Substitute values from the question.

$$I_p \times 230\ \text{V} = 3\ \text{A} \times 9\ \text{V}$$

Step 4: Rearrange and solve for I_p.

$$I_p = \frac{3\,\text{A} \times 9\,\text{V}}{230\,\text{V}}$$
$$= 0.12\,\text{A}$$

Answer

So, the current supplied to the primary coil is 0.12 A.

In stepping down the voltage, the transformer has stepped up the current. If both had been stepped up, we would be getting something for nothing – which in physics, is impossible!

Questions

P7.18 A power station generates 230 000 W.

- **a** Calculate the current in the wires when the power is transmitted:
  - **i** at 230 V
  - **ii** at 23 000 V.
- **b** Explain why it is better to transmit the electricity at a higher voltage.

P7.19 The power supply to a factory is 100 kW. The wires have a resistance of 0.2 Ω.

- **a** Calculate the power loss in the cables when the voltage across the wires is 250 V.
- **b** Calculate the power loss when the voltage is stepped up to 12 500 V.

P7.20 A transformer reduces the mains voltage from 240 V to 12 V for use in a school laboratory power pack. The current supplied by the power pack is 2 A. What current flows into the power pack? What assumption must you make in this calculation?

REFLECTION

Look back through your work on the motor effect and electromagnetic induction. Are there any areas you need to work on? Ask yourself:

- Are you clear about what each effect is?
- Can you recall and understand the equations?
- Can you recall and use the relevant rules for finding directions of fields or currents?

Make revision cards with the key things you need to remember.

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PROJECT P7.01 POWER TO THE PEOPLE

In this Swedish town, coal is mined then burnt to generate electricity. The electricity is distributed to homes via the national grid.

Electrical power generation and distribution varies depending on where you live.

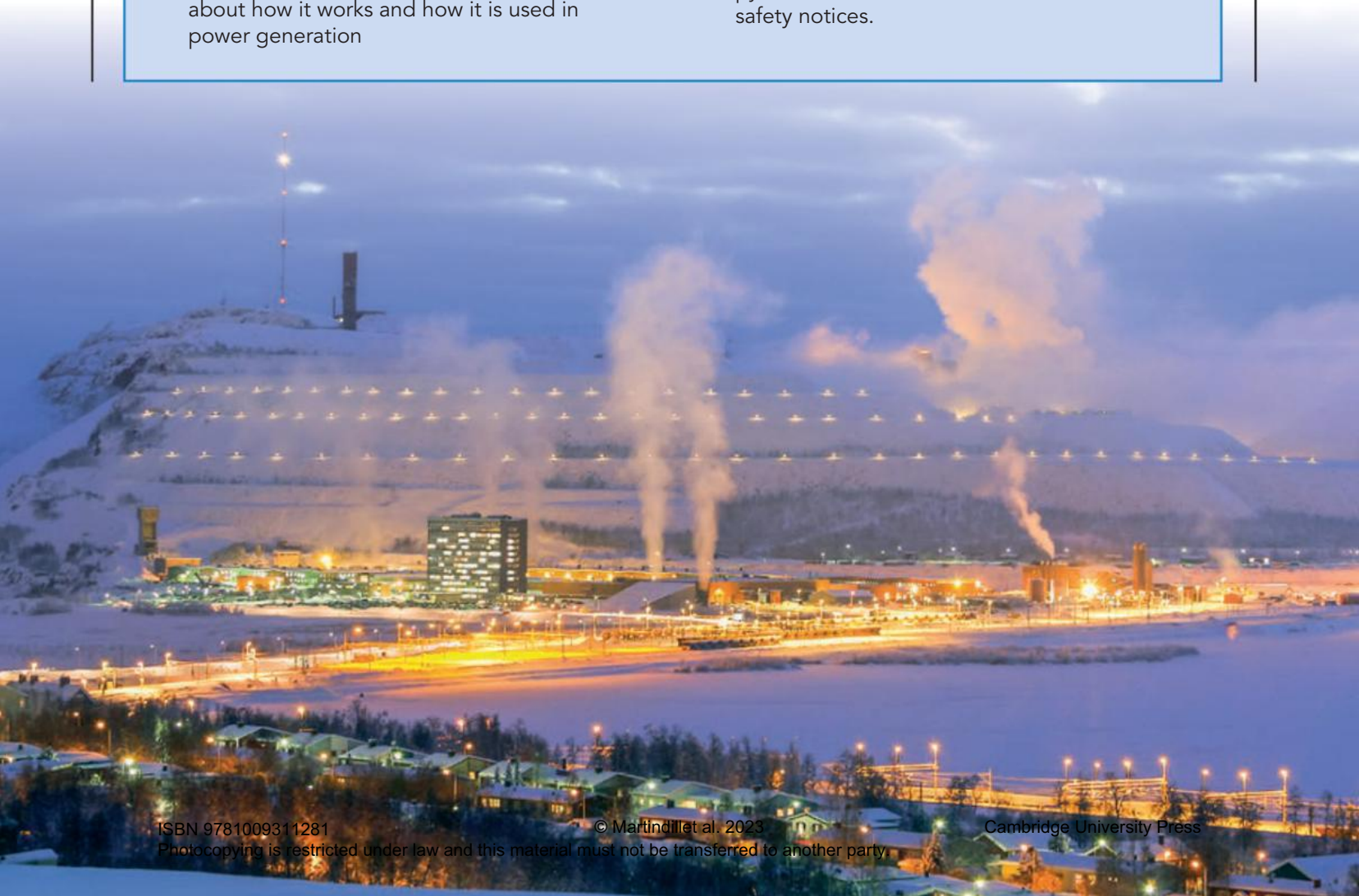
Your task is to research how electricity reaches you. Working in a small group you will research how electricity is generated and distributed in your country. You will work together to produce a large poster illustrating and explaining what you find. Your poster will have a lot of information, so plan carefully how the different parts will come together. For example, you may decide to structure your poster around a diagram of the national grid, with information boxes for each stage.

You must include:

- information about the type of power stations and renewable resources which are in use
- a diagram of a generator and information about how it works and how it is used in power generation
- a diagram similar to Figure P7.22 showing how electricity is distributed
- information about the role of transformers in the system and the difference between step-up and step-down transformers
- reasons why the voltage of the supply has to be changed.

You could add:

- a pie chart showing the different energy resources used in your country
- a detailed explanation of how an a.c. generator works, including why the current generated is a.c. (not d.c.)
- details of the voltages at different parts of the grid, with calculations showing the transformers needed at each stage
- photographs from your local area showing pylons, substations, overhead cables and safety notices.



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SUMMARY

There is a magnetic field around a current-carrying conductor.
The strength and direction of the field depends on the size and direction of the current.
When a current flows through a conductor in a magnetic field, there is a force on the conductor. This is called the motor effect.
The direction of the force can be reversed by reversing the field or the current.
A coiled conductor in a magnetic field experiences a turning force. This is the basis of the electric motor.
The strength of a motor can be increased by increasing the field, the current or the number of turns on the coil.
Fleming's left-hand rule allows you to find the direction of the force on a current-carrying conductor.
An electric motor uses a split-ring commutator to produce continuous rotation.
When there is relative movement between a conductor and a magnetic field, an e.m.f. is induced across the conductor. The induced e.m.f. may cause an induced current to flow.
The e.m.f. induced in a coil of wire can be increased by: • increasing the magnetic field strength • increasing the number of turns on the coil • increasing the speed of movement.
The output of an a.c. generator depends on the position of the coil in relation to the magnetic field.
A transformer, consisting of a primary coil, a secondary coil and a soft iron core can be used to change alternating voltages.
A step-up transformer increases voltage, a step-down transformer decreases voltage.
The number of turns on transformer coils and the voltages across them can be calculated using the equation $\frac{V_p}{V_s} = \frac{N_p}{N_s}$
Transformers increase voltage for transmission by the national grid then reduce the voltage to a safer level for consumers.
When a transformer is assumed to be 100% efficient, the primary and secondary currents and voltages are related by the equation $I_p \times V_p = I_s \times V_s$
The power losses in cables can be calculated using the equation $P = I^2R$

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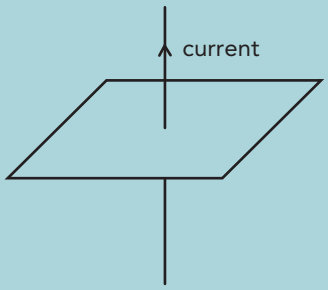
PRACTICE QUESTIONS

1 Current flows up a wire as shown in the diagram. **Identify** what the magnetic field will look like, when viewed from above.

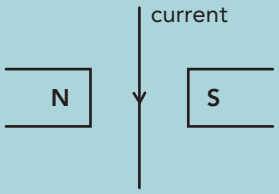


A straight lines from left to right
B straight lines from right to left
C clockwise circles
D anticlockwise circles [1]

2 Identify which of the following pairs of changes will *both* increase the strength of an electric motor.

A reversing the magnetic field and increasing the number of turns on the coil
B increasing the number of turns on the coil and reversing the direction of the current
C reversing the direction of the current and reversing the magnetic field
D using a more powerful magnet and increasing the number of turns on the coil [1]

3 Current is passed through a wire in a magnetic field.



The wire experiences a force.

a **Give** the rule which allows you to find the direction of the force. [1]
b Use this rule to **determine** the direction of the force on the wire. [1]
[Total: 2]

4 A school laboratory power supply contains a step-down transformer.

a Give the name of the coil that has more turns in a step-down transformer. [1]
b **State** what a step-down transformer does to the voltage. [1]
c State what a step-down transformer does to the current. [1]
[Total: 3]

5 A student investigates the effect of moving a bar magnet into a coil.
She measures the current which flows in the coil when she moves the magnet.
Describe *two* ways that she could increase the current. [2]

COMMAND WORD

identify: name/select/recognise.

COMMAND WORDS

give: produce an answer from a given source or recall/memory.

determine: establish an answer using the information available.

state: express in clear terms.

describe: state the points of a topic/give characteristics and main features.

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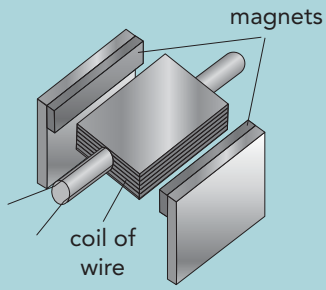
CONTINUED

6 The diagram shows the main part of a simple direct current electric motor.



a Name and **define** the rule which is needed to work out the direction the motor will move. **[2]**

b An important part of the motor is missing from the diagram. Name it and state its function. **[2]**

c **Suggest** *two* ways to increase the strength of the motor. **[2]**

[Total: 6]

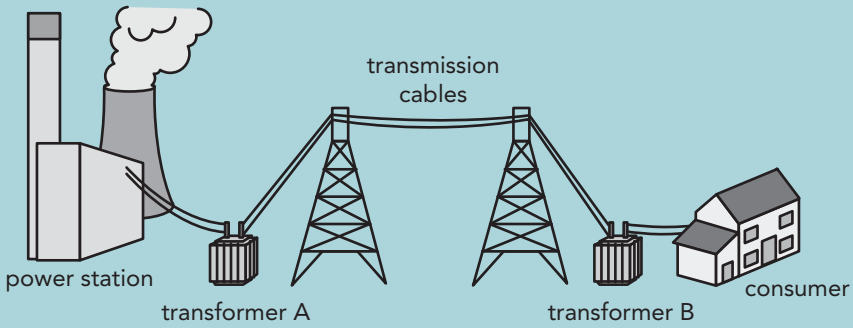
7 **a** **Sketch** a step-up transformer and label its three essential parts. **[4]**

b A student connects the input of a step-up transformer to a battery. He connects the output to a bulb, but it does not light.

Explain why the lamp does not light. **[1]**

[Total: 5]

8 **a** Transformers are used in the national grid to change the voltage of the supply. For transformers A and B, state whether the transformer is step-up or step-down, and explain why the voltage change is necessary. **[4]**



b A transformer in the national grid has 800 turns on the primary coil and 16 000 on the secondary. The primary voltage is 25 kV.

Calculate the secondary voltage. **[2]**

[Total: 6]

COMMAND WORDS

define: give a precise meaning.

suggest: apply knowledge and understanding to situations where there is a range of valid responses in order to make proposals/put forward considerations.

sketch: make a simple freehand drawing showing the key features, taking care over proportions.

explain: set out purposes or reasons; make the relationships between things clear/say why and/or how and support with relevant evidence.

COMMAND WORD

calculate: work out from given facts, figures or information.

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CONTINUED

9 A teacher demonstrates electromagnetic induction using a coil, a bar magnet and a sensitive, centre-zero ammeter.

a The teacher slowly moves the magnet towards the coil. State and explain what happens. **[2]**

b The teacher changes different factors in the experiment.
State the effect of each of these actions on the ammeter reading:

i The teacher holds the coil still. **[1]**

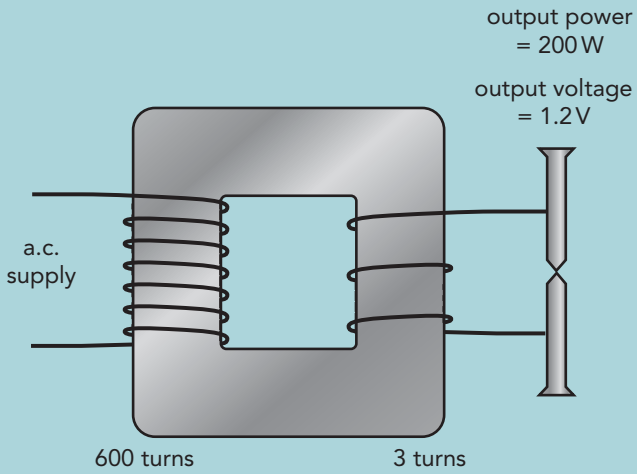
ii The teacher moves the magnet quickly towards the coil. **[1]**

iii The teacher holds the magnet still and slowly moves the coil towards the magnet. **[1]**

iv The teacher quickly moves the magnet away from the coil. **[1]**

[Total: 6]

10 Spot welding is a method of joining two pieces of metal together by passing a very high current through them. The diagram shows a transformer being used to spot weld two iron nails.



a Explain why the nails become hot when the power is switched on. **[1]**

b Use the data from the diagram to calculate the current needed from the power supply. Assume the transformer is 100% efficient.
Give your answer to two decimal places. **[4]**

[Total: 5]

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SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
describe the field around a straight wire and a solenoid when they carry current	P7.01			
describe the factors that affect the direction and strength of these fields	P7.01			
state that a current-carrying conductor in a magnetic field experiences a force	P7.02			
use Fleming's left-hand rule to find the direction of this force	P7.02			
list three ways of increasing the strength of an electric motor	P7.03			
describe how an electric motor produces a turning effect, including the function of the brushes and split-ring commutator	P7.03			
state that an e.m.f. is induced when there is relative movement between a conductor and a magnetic field, and describe an experiment to demonstrate this	P7.04			
list the ways in which the induced e.m.f. can be increased	P7.04			
describe the structure and operation of an a.c. generator	P7.05			
sketch a graph of voltage against time for an a.c. generator; state what position the coil must be in for the peaks, troughs and zeros on the graph	P7.05			
list the three essential parts of a transformer	P7.06			
describe the difference between a step-up and a step-down transformer, by comparing their primary and secondary coils	P7.06			
recall and use the equation $\frac{V_p}{V_s} = \frac{N_p}{N_s}$	P7.06			
describe how and why transformers are used in high-voltage transmission	P7.06			
recall and use the equation $I_p \times V_p = I_s \times V_s$	P7.06			
recall and use the equation $P = I^2R$	P7.06			

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P8

Nuclear physics

Only learners entered for Co-ordinated Core and Co-ordinated Supplement study this content

IN THIS CHAPTER YOU WILL:

- describe the structure of the atom
- name and state the mass and charge of the particles in the nucleus
- represent nuclei in the form ${}^{A}_{Z}X$
- explain what isotopes are
- describe fission and fusion reactions
- explain the term 'background radiation' and list some of its sources
- describe how ionising nuclear radiation is measured
- describe the nature and behaviour of alpha, beta and gamma radiation
- describe some practical uses of radioactive emissions
- describe radioactive decay
- use nuclide notation to write equations for radioactive decay
- define and calculate radioactive half-life
- consider the safety issues around ionising nuclear radiation.

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BEFORE YOU START

With a partner, spend two minutes making notes on what you know about atoms. Include a sketch of an atom.

Now discuss these statements and decide which are true and which are false:

1 Atoms are the smallest particles there are.
2 There are 92 different types of atom.
3 Most of the mass of an atom is in the nucleus.
4 Atoms have no charge.

SCIENCE IN CONTEXT P8.01

The radium girls

Radioactivity was first discovered in 1896. Soon afterwards, in 1898, Marie Curie discovered radium which was found to be useful in treating cancer. It was assumed that these emissions which could cure cancer, must be healthy. Radium was used to treat any conditions where the patient seemed to need more energy, from anaemia to impotence. An industry developed selling products such as radioactive water, toothpaste and face creams to give you a 'healthy' glow. Figure P8.01 shows an advert for such a cream.

Figure P8.01: The name Tho-Radia refers to the radioactive isotopes of thorium and radium used in this face cream.

Radium was used in paint which converted the radiation it emitted into light. The process is called luminescence. This was used to make watch and clock faces visible in the dark.

The radium was painted on to these watches by young women in factories (Figure P8.02). These jobs were popular as radium was a glamorous, expensive product and the work was much cleaner than other factory work. The women used camel hair brushes to apply the radioactive paint. They were told to squeeze these brushes between their lips as they worked to keep a fine point on the brush.

These instructions came from factory owners who knew that research was beginning to show that radium was a dangerous substance and so limited their own exposure to it. Some workers questioned whether the radium was safe and were reassured that they were not at risk.

Figure P8.02: The radium girls painted luminous radioactive paint on clock and watch faces.

Radium is chemically similar to calcium and the radium replaced calcium in the bones of the women, weakening and damaging their bones. They experienced pain and many – probably thousands – developed bone and other cancers which were often fatal. When the women began to die, some factory owners tried to blame their deaths on a virus, or on syphilis.

Eventually the women won a court case in 1928 and the survivors received compensation, though the companies appealed, and it was only in 1939 that the case was finally won. Luminous watches were still sold until the 1960s, though the painting techniques were changed.

Discussion questions

1 Why did the factory owners not inform the workers about the dangers of working with radium?
2 Do you think this situation could happen today? Consider ways in which laws and access to information may have made this less likely.

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P8.01 The nuclear atom

At one time, science textbooks would have said that atoms are too tiny to be seen. In 1911 Rutherford discovered that the atom contains a tiny dense nucleus.

We now know that the atom contains a nucleus made up of two types of particles, **protons** and **neutrons**. The protons carry the positive charge of the nucleus, while the neutrons are neutral. Negatively charged electrons orbit the positively charged nucleus. Protons and neutrons have similar masses, and they account for most of the mass of the atom because electrons are so light. Together, protons and neutrons are known as **nucleons** (Figure P8.03).

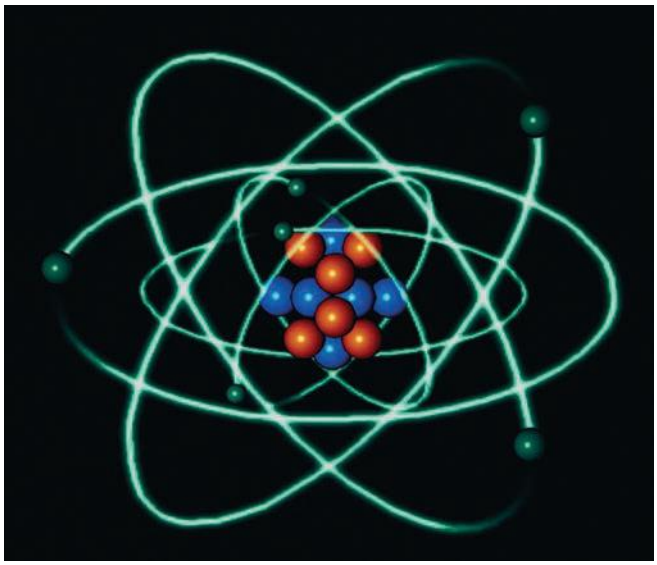

Figure P8.03: The nuclear model of the atom. Six electrons are illustrated orbiting a nucleus made up of six protons and six neutrons.

Table P8.01 summarises information about the three sub-atomic particles and their charges. The **relative charge** gives the charge of each particle compared to that of a proton. It is much easier to remember these values, rather than the actual values in coulombs (C).

Particle	Position	Relative charge
proton	in nucleus	+1
neutron	in nucleus	0
electron	orbiting nucleus	−1

Table P8.01: Charges and positions of the three sub-atomic particles.

Nuclide notation

Nuclide notation is a shorthand way of describing the number of protons and neutrons in a nucleus.

An example is the helium nucleus:

$$^{4}_{2}\mathrm{He}$$

This tells us the following information:

- The chemical element. The letters He are the chemical symbol for helium.
- The number of protons. The bottom number is the proton number (also known as the atomic number). This nucleus contains two protons.
- The number of nucleons. The top number is the nucleon number (also known as the mass number). This nucleus contains four nucleons. We know that two of these are protons, so we can deduce that the other two are neutrons.

We can write the general symbol for an element (X) with its **proton number (Z)**, which is the number of protons in the nucleus, and **nucleon number (A)**, which is the number of nucleons (protons and neutrons) in the nucleus, as follows:

$$^{A}_{Z}\mathrm{X}$$

This is known as nuclide notation.

A neutral atom of element X will also have Z electrons orbiting the nucleus.

KEY WORDS

proton: a positively charged particle found in the atomic nucleus.

neutron: an uncharged particle found in the atomic nucleus.

nucleon: a particle found in the atomic nucleus; a proton or a neutron.

relative charge: the charge of a particle relative to the charge of a proton.

proton number (Z): (or atomic number) the number of protons in an atomic nucleus.

nucleon number (A): (or mass number) the number of nucleons (protons and neutrons) in an atomic nucleus.

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WORKED EXAMPLE P8.01

What can you deduce about the atom whose nucleus can be represented by $^{14}_{6}C$?

Step 1: Look at the atomic symbol.

The symbol C tells us it is a carbon nucleus.

Step 2: Identify the number of protons:

$Z = 6$

Step 3: Identify the number of electrons.

It is a neutral atom, so it has the same number of protons as electrons = 6.

Step 4: Calculate the number of neutrons:

$N = A - Z = 14 - 6 = 8$

Answer

$^{14}_{6}C$ is a carbon nucleus with six protons, six electrons and eight neutrons.

REFLECTION

What strategies have you found useful in remembering the properties of each of the sub-atomic particles and the definitions of nucleon and proton numbers? Share your strategies with a partner.

Questions

P8.01 Copy and complete these sentences:

An atom has a tiny, dense _____. This contains positively charged _____ and neutral _____.

These two particles have approximately the same _____.

A nucleus can be described by two numbers: the proton number, and the nucleon number which is the total number of _____ and _____ in the nucleus.

P8.02 A particular neutral atom of boron is represented by $^{12}_{5}B$.

a What is its proton number?

b What is its nucleon number?

c Write down the numbers of protons, neutrons and electrons it contains.

P8.03 A cobalt atom contains 33 neutrons.

a Use the Periodic Table to find its proton number.

b Write down an expression in the form $^{A}_{Z}X$ to represent the cobalt nucleus.

Elements and isotopes

The atoms of all elements exist in more than one form. For example, Figure P8.04 shows three types of hydrogen atom. Each has just one proton in its nucleus. This tells us that all these atoms are hydrogen. However, they have different numbers of neutrons (0, 1 and 2). This means that they are described as different **isotopes** of hydrogen.

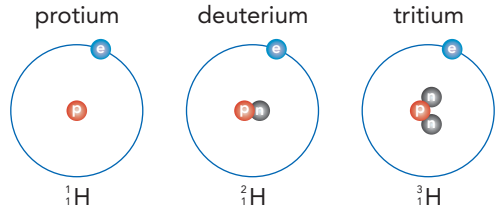

Figure P8.04: Hydrogen exists in three different forms, known as isotopes. All three have the same proton number.

- The different isotopes of an element all have the same chemical properties, but those with a greater number of neutrons are heavier.
- The different isotopes of an element all have the same number of protons but different numbers of neutrons in their nuclei.

KEY WORD

isotope: isotopes of an element have the same proton number but different nucleon numbers.

Table P8.02 shows atoms of two isotopes of helium, $^{4}_{2}He$ (the most common isotope) and $^{3}_{2}He$ (a lighter and much rarer isotope). Each $^{3}_{2}He$ has two protons in the nucleus and two electrons orbiting it, but the lighter isotope has only one neutron. These isotopes are referred to as helium-4 and helium-3.

Symbol for isotope	Proton number Z	Neutron number N	Nucleon number A
$^{4}_{2}He$	2	2	4
$^{3}_{2}He$	2	1	3

Table P8.02: Isotopes of helium.

Table P8.03 shows two isotopes of uranium. Uranium-238 is the most common isotope. Uranium-238 has three more neutrons than uranium-235, but the same number of protons. Uranium-235 is used in nuclear power stations as its nuclei can be split to release a huge amount of energy.

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Symbol for isotope	Proton number Z	Neutron number N	Nucleon number A
$^{235}_{92}U$	92	143	235
$^{238}_{92}U$	92	146	238

Table P8.03: Isotopes of uranium.

All elements have isotopes, some as many as 36. For most chemical elements, at least one isotope is stable. Other isotopes are often unstable. This means that the nucleus is likely to give out radioactivity in order to become stable. These isotopes are described as radioactive.

Questions

P8.04 Carbon exists in two forms $^{12}_{6}C$ and $^{14}_{6}C$.

- **a** Write down the number of protons, neutrons and electrons in each.
- **b** Copy and complete these sentences:

  $^{12}_{6}C$ and $^{14}_{6}C$ are two _____ of carbon.

  They have the same _____ number, but different _____ numbers.

  Both have the same _____ properties.

P8.05 Table P8.04 lists the proton and nucleon numbers of six different nuclei.

- **a** Copy and complete the table by filling in the empty spaces.
- **b** Which *three* nuclei are isotopes of one element?
- **c** Which *two* nuclei are isotopes of another element?
- **d** Use a Periodic Table to identify the three elements in Table P8.04.

Nucleus	Proton number Z	Neutron number N	Nucleon number A
Nu-1	6	6	
Nu-2		6	13
Nu-3	7		14
Nu-4		8	14
Nu-5		6	11
Nu-6		7	13

Table P8.04: Proton and nucleon numbers of nuclei.

The charge on a nucleus

The charge on a nucleus is equal to the number of protons, because each proton has a relative charge of +1. So the nuclei of all three isotopes of hydrogen have a charge of +1, as all contain just one proton.

Question

P8.06 Write down the charge of the nuclei of the isotopes shown in Table P8.04.

Nuclear fission and fusion

In Chapter P2 you learnt about the use of nuclear fuels. These produce energy by splitting nuclei which is a process known as nuclear fission. Figure P8.05 shows a fission reaction in which a uranium-235 nucleus is hit by a neutron. The extra neutron causes it to become unstable and it splits, making two new nuclei and three extra neutrons. A large amount of energy is also released. These neutrons can then split, leading to a chain reaction.

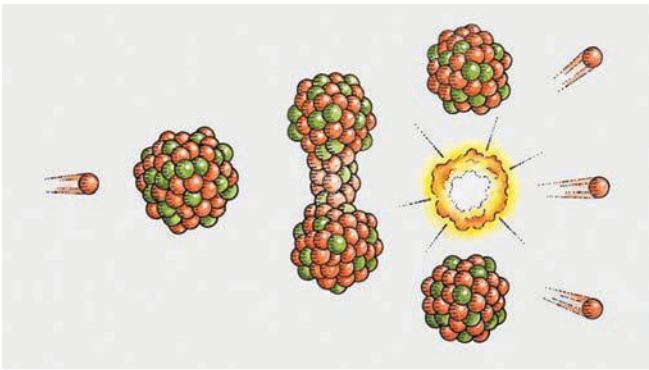

Figure P8.05: A uranium-235 nucleus being split to make barium and krypton nuclei, three more neutrons and a lot of energy.

Nuclear fusion produces even more energy than nuclear fission. Fusion is when two nuclei join together to form a larger nucleus. This can only happen at extremely high temperatures. Fusion is the process by which stars produce heat and light.

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P8.02 Radioactivity

Detection of radioactivity

Ionising nuclear radiation and background radiation

Some isotopes are unstable and their nuclei emit **radiation** to become more stable. The radiation emitted from unstable nuclei is called **ionising nuclear radiation**. This is high energy radiation which can knock electrons from atoms, so they become ions. Unstable nuclei like this are called radioactive.

Many naturally occurring substances are **radioactive substances**. Usually the radiation in these substances is not very concentrated, so they do not cause a problem.

In fact, we are exposed to low levels of radiation all the time. This is known as **background radiation**. In addition, we may be exposed to radiation from artificial sources, such as the radiation we receive if we have a medical X-ray.

KEY WORDS

radiation: energy spreading out from a source carried by particles or waves.

ionising nuclear radiation: radiation emitted by the nucleus which can cause ionisation: alpha particles, beta particles or gamma rays.

radioactive substance: a substance that decays by emitting radiation from its atomic nuclei.

background radiation: the radiation from the environment to which we are exposed all the time.

Sources of background radiation

Figure P8.06 shows the different sources that contribute to the average dose of radiation received by people across the world. It is divided into natural background radiation (about 85%) and radiation from artificial sources (about 15%).

Natural background radiation

The air is radioactive. It contains a radioactive gas called radon, which seeps up to the Earth's surface from radioactive uranium rocks underground. Because we breathe in air all the time, we are exposed to radiation from this substance. (This varies widely from country to country, and from one part of a country to another, depending on how much uranium there is in the underlying rocks.)

The ground contains radioactive substances. We use materials from the ground to build our houses, so we are exposed to radiation from these.

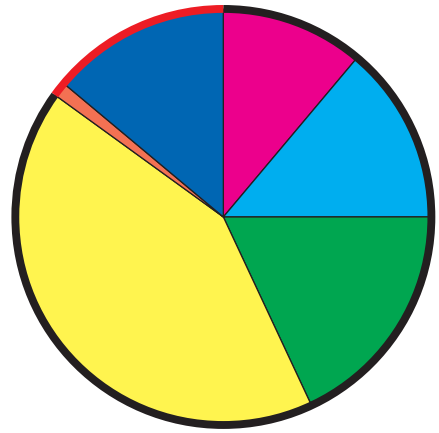

Figure P8.06: This pie chart shows the different sources of radiation and how they contribute to the average dose of radiation received each year by an individual. Only about 15% comes from non-natural sources.

Our food and drink are also slightly radioactive. Living things grow by taking in materials from the air and the ground. Some of these materials are radioactive, so the plants which feed into our food chains will also be slightly radioactive.

Finally, radiation reaches us from space in the form of cosmic rays. Some of this radiation comes from the Sun, some from further out in space. Most cosmic rays are stopped by the Earth's atmosphere. If you live up a mountain, you will be exposed to more radiation from this source.

Background radiation from artificial sources

Most radiation from artificial sources comes from medical sources. This includes the use of X-rays and gamma rays for seeing inside the body, and the use of radiation for destroying cancer cells. There is always a danger that exposure to such radiation may damage cells. Medical physicists are always working to reduce the levels of radiation used in medical procedures. Overall, many more lives are saved than lost through this beneficial use of radiation.

Today, most nuclear weapons testing is done underground. In the past, bombs were detonated on land or in the air, and this contributed much more to the radiation dose received by people around the world.

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When you fly in an aircraft, you are high in the atmosphere. You are exposed to more cosmic rays. This is not a serious problem for the occasional flier, but aircraft crews have to keep a check on their exposure.

Many people, such as medical radiographers and staff in a nuclear power station, work with radiation. Overall, a power station does not add much to the national average dose, but for individuals who work there it can increase their dose by up to 10%.

Finally, small amounts of radioactive substances escape from the nuclear industry, which processes uranium for use as the fuel in nuclear power stations and handles the highly radioactive spent fuel after it has been used.

Geiger counters

Radiation can be measured using a Geiger counter. This consists of a detector called a GeigerMüller tube which detects radiation, connected to a counter (Figure P8.07). The counter records the rate at which radiation is detected. This is known as the **count rate** and it is measured in counts per second (count/s) or counts per minute (count/min).

Figure P8.07: Using a Geiger counter to monitor radiation levels in crops.

KEY WORDS

count rate: the number of decaying radioactive atoms detected each second (or minute, or hour).

Questions

P8.07 What is meant by the term 'background radiation'?

P8.08 Name *three* sources of natural background radiation and *three* sources of artificial background radiation.

P8.09 Which type of natural background radiation are airline crews exposed to more than most people?

Three types of nuclear emission

There are three types of ionising radiation emitted by radioactive substances. These are named after the first three letters of the Greek alphabet, alpha (α), beta (β) and gamma (γ).

The different types of radiation have different properties and therefore different uses and dangers. Table P8.05 summarises the properties of the three types.

- An **alpha particle (α-particle)** is made up of two protons and two neutrons. This is the same as the nucleus of a helium atom. Alpha is easily stopped (see Figure P8.08) and causes a lot of ionisation.
- A **beta particle (β-particle)** is a high-speed electron. Beta can be stopped by aluminium and is weakly ionising.
- A **gamma ray (γ-ray)** is a form of electromagnetic radiation with a very short wavelength and high frequency. Gamma can be reduced, but not stopped, by thick lead. It is only weakly ionising.

KEY WORDS

alpha particle (α-particle): a particle made up of two protons and two neutrons; it is emitted by an atomic nucleus during radioactive decay.

beta particle (β-particle): a high-speed electron that is emitted by an atomic nucleus during radioactive decay.

gamma ray (γ-ray): electromagnetic radiation emitted by an atomic nucleus during radioactive decay.

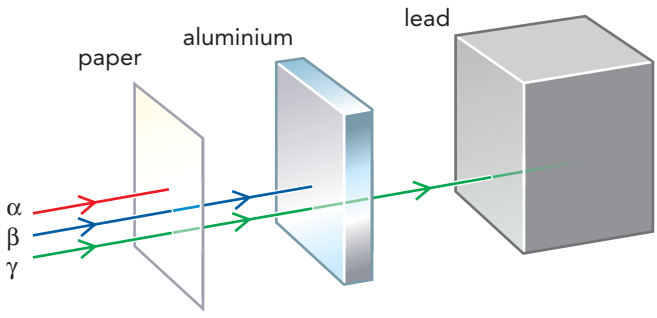

Figure P8.08: The penetrating abilities of ionising nuclear radiations.

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Name	Nature	Penetration	Ionising effect
alpha α	2 protons + 2 neutrons	stopped by approximately 5 cm of air or a few sheets of paper	strongly ionising
beta β	an electron	stopped by a thin sheet of aluminium	weakly ionising
gamma γ	electromagnetic radiation	reduced by thick lead, but not completely stopped	very weakly ionising

Table P8.05: Three types of radiation produced by naturally occurring radioactive substances.

Radioactive decay

Not all nuclei give out radiation. Some nuclei are unstable and give out alpha, beta or gamma radiation in order to become more stable. This process is known as **radioactive decay**.

If you listen to the clicks or beeps of a Geiger counter, you may notice that it is impossible to predict when the next sound will come. This is because radioactive decay is a **random process**. Radioactive substances contain unstable nuclei which will decay spontaneously. We cannot predict which nucleus will decay next or when this will happen. The direction in which the radiation will be emitted is also random. Radioactive decay is not affected by external factors such as temperature.

An atom of a radioactive substance emits either an α-particle or a β-particle. In addition, it may emit some energy in the form of a γ-ray. The γ-ray is usually emitted at the same time as the α-particle or β-particle, but it may be emitted some time later. Figure P8.09 shows the different types of radioactive decay.

KEY WORDS

radioactive decay: the emission of alpha, beta or gamma radiation from an unstable nucleus.

random process: a process that happens at a random rate and in random directions; the timing and direction of the next emission cannot be predicted.

alpha decay: the decay of a radioactive nucleus by the emission of an α-particle.

beta decay: the decay of a radioactive nucleus by the emission of a β-particle.

When an atom of a radioactive substance decays by **alpha decay** or **beta decay**, it becomes an atom of another element. This is because the number of protons in the nucleus changes.

You may be wondering how a beta particle (an electron) can be emitted from the nucleus as there are no electrons in the nucleus. To understand this, imagine a neutron being made up of an electron and a proton stuck together. When decay happens, the proton and electron separate, and the electron is emitted from the nucleus. The nucleus therefore loses a neutron and gains a proton.

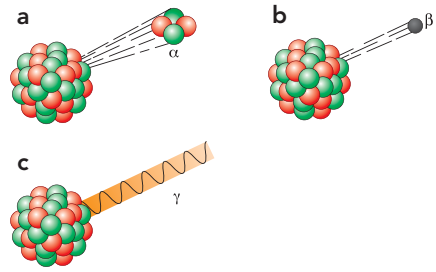

Figure P8.09 a: Alpha emission. **b:** Beta emission. **c:** Gamma emission.

Questions

P8.10 Copy and complete the following sentences.

Radioactive decay happens when a nucleus is _____.

An α-particle consists of _____ _____ and _____ _____. A β-particle is an _____. γ-radiation is a form of high-frequency _____ radiation.

P8.11 A β-particle is identical to an electron. How is it different to most electrons?

P8.12 Which type of radiation travels at the speed of light?

Radioactive decay equations

Radioactive decay can be described using balanced equations using nuclide notation. To write these equations we need to consider the effect of each emission on the nucleus emitting it:

- α-decay: two protons and two neutrons are emitted. The proton number decreases by 2 and the nucleon number decreases by 4.
- β-decay: a neutron splits into a proton and an electron; the electron is emitted. The proton number increases by 1 and the nucleon number remains the same.
- γ-decay: this is the emission of energy from the nucleus and it does not change the particles in the nucleus.

These changes all lead to the nucleus becoming more stable.

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Here is an example of an equation for *alpha decay*:

$$^{241}_{94}\text{Am} \rightarrow {}^{237}_{92}\text{U} + {}^{4}_{2}\text{He} + \text{energy}$$

This represents the decay of americium-241, the isotope used in smoke detectors. It emits an α-particle (represented as a helium nucleus) and becomes an isotope of uranium. An α-particle can be represented as $^{4}_{2}\text{He}$ or $^{4}_{2}\alpha$.

Notice that the numbers in this equation must balance because we cannot lose mass or charge. So:

nucleon numbers: $241 \rightarrow 237 + 4$

proton numbers: $294 \rightarrow 92 + 2$

WORKED EXAMPLE P8.02

A radioisotope of thorium ($^{229}_{90}\text{Th}$) decays by emitting an α-particle. The resulting nucleus is also unstable and emits a beta particle. Write equations for the two emissions.

Step 1: In α-emission ($^{4}_{2}\alpha$) the proton number decreases by 2 (in this case, from 90 to 88). From the Periodic Table, we can see that radium (Ra) has the proton number 88.

The nucleon number decreases by 4 (in this case, from 229 to 225).

Step 2: In β-emission ($^{0}_{-1}\beta$) the proton number increases by 1 (in this case from 88 to 89). From the Periodic Table, we can see that actinium (Ac) has the proton number 89.

The nucleon number remains the same.

Answer

α-emission: $^{229}_{90}\text{Th} \rightarrow {}^{225}_{88}\text{Ra} + {}^{4}_{2}\alpha$

β-emission: $^{225}_{88}\text{Ra} \rightarrow {}^{225}_{89}\text{Ac} + {}^{0}_{-1}\beta$

Here is an example of an equation for *beta decay*:

$$^{14}_{6}\text{C} \rightarrow {}^{14}_{7}\text{N} + {}^{0}_{-1}\text{e} + \text{energy}$$

This is the decay that is used in radiocarbon dating. A carbon-14 nucleus decays to become a nitrogen-14 nucleus. The β-particle, an electron, is represented by $^{0}_{-1}\text{e}$ or $^{0}_{-1}\beta$. If we could see inside the nucleus, we would see that a single neutron has split into a proton and an electron. So:

$$^{1}_{0}\text{n} \rightarrow {}^{1}_{1}\text{p} + {}^{0}_{-1}\text{e}$$

For each of these two β-decay equations, you should be able to see that the nucleon numbers and proton numbers are balanced. In radioactive decay, nucleon number and proton number are conserved.

Questions

P8.13 Explain why emission of α- or β-particles changes the nucleus to one of a different element.

P8.14 The equation represents the decay of a polonium nucleus to form a lead nucleus. An α-particle is emitted.

$^{210}_{84}\text{Po} \rightarrow {}^{206}_{82}\text{Pb} + \square\square + \text{energy}$

a Copy and complete the equation.

b Show that the proton numbers are equal on each side of the equation.

c Show that the nucleon numbers are equal on each side of the equation.

P8.15 Write a balanced nuclear equation to show what happens to the polonium isotope $^{218}_{84}\text{Po}$ when it emits a β-particle.

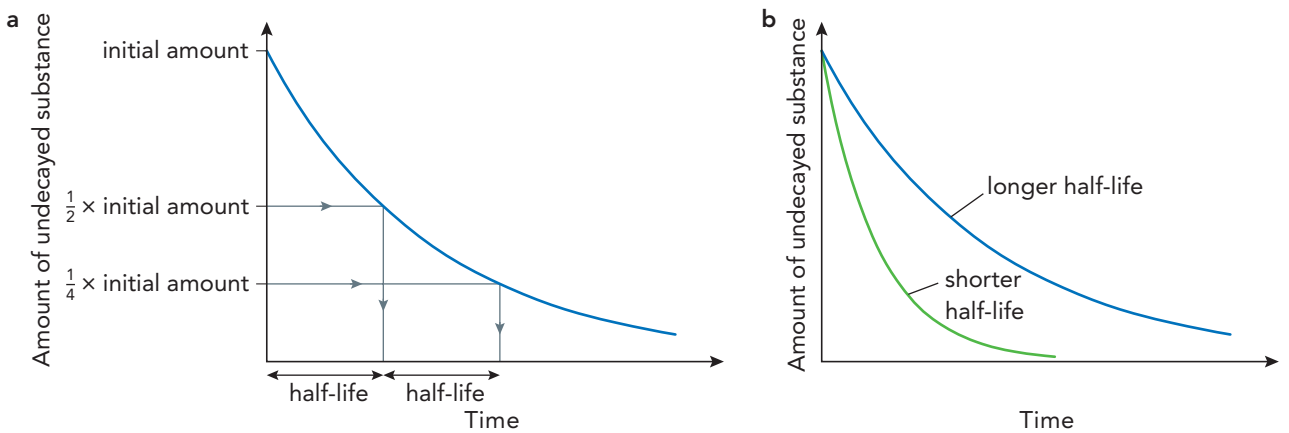

Figure P8.10 a: A decay graph for a radioactive substance. **b:** A steeper graph shows that a substance has a shorter half-life.

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Activity and half-life

The **activity** of a radioactive source is the rate at which its nuclei decay. This can be monitored using a Geiger counter which measures the count rate (the number of emissions detected each second).

The activity of a source decreases with time. As nuclei decay and become stable, there are fewer unstable nuclei, so there are fewer decays each second. The count rate decreases following the same pattern as the number of undecayed atoms.

All radioactive substances decay with the same pattern, as shown in Figure P8.10.

The graph shows that the amount of a radioactive substance decreases rapidly at first, and then more and more slowly. In fact, because the graph tails off more and more slowly, we cannot say when the last atoms will decay. Different radioactive substances decay at different rates, some much faster than others, as shown in Figure P8.10b.

We cannot say when the substance will have entirely decayed. We have to think of another way of describing the rate of decay. As shown on the graph in Figure P8.10a, we identify the **half-life** of the substance.

The half-life of a radioactive isotope is the average time taken for half of the atoms in a sample to decay, or the time for its activity or count rate to halve.

Half-lives can vary from a fraction of a second to thousands of years. Uranium decays slowly because it has a very long half-life. The radioactive samples used in schools usually have half-lives of a few years, so that they have to be replaced when their activity has dropped significantly. Some radioactive substances have half-lives that are less than a microsecond. No sooner are they formed than they decay into something else.

KEY WORDS

activity: the rate at which nuclei decay in a sample of a radioactive substance.

half-life: the average time taken for half the atoms in a sample of a radioactive material to decay.

Explaining half-life

After one half-life, half of the atoms in a radioactive sample have decayed. However, this does not mean that all of the atoms will have decayed after two half-lives. From the graph of Figure P8.10a, you can see that one-quarter will still remain after two half-lives. Why is this?

Figure P8.11 shows one way of thinking about what is going on. Imagine that we start with a sample of 100 undecayed atoms of a radioactive substance (white circles in Figure P8.11a). They decay randomly (black circles in Figure P8.11b–d). Each undecayed atom has a 50% chance of decaying in the course of one half-life. So, looking at the panels in Figure P8.11, we can describe the decay like this:

- At the start, in Figure P8.11a, there are 100 undecayed atoms.
- After one half-life, in Figure P8.11b, a random selection of 50 atoms has decayed.
- During the next half-life, in Figure P8.11c, a random selection of half of the remaining 50 atoms decays, leaving 25 undecayed.
- During the third half-life, in Figure P8.11d, half of the remaining atoms decay, leaving 12 or 13. (Of course, you cannot have half an atom.)

So the number of undecayed atoms goes 100, 50, 25, 12, … and so on. It is because radioactive atoms decay in a random fashion that we get this pattern of decay. Notice that, just because one atom has not decayed in the first half-life does not mean that it is more likely to decay in the next half-life. The process is completely random.

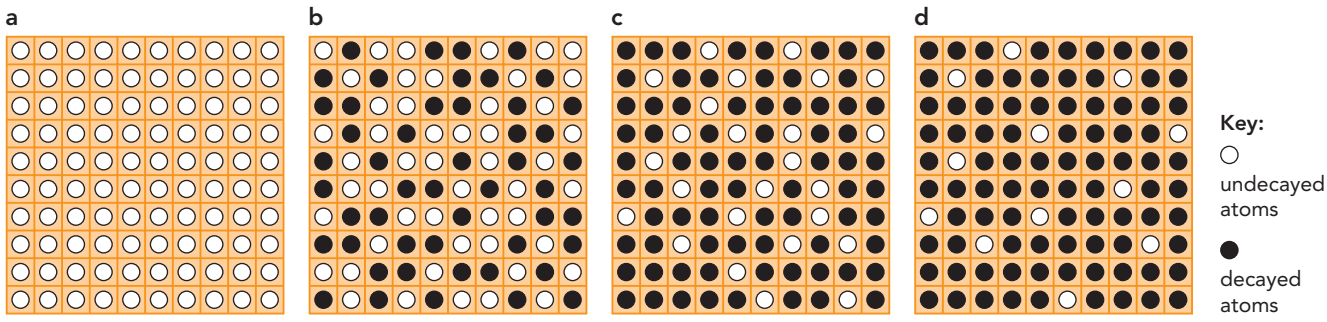

Figure P8.11: The pattern of radioactive decay comes about because the decay of individual atoms is random. Half of the atoms decay during each half-life, but we have no way of predicting which individual atoms will decay.

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WORKED EXAMPLE P8.03

The count rate from a radioactive source is recorded for ten days. Figure P8.12 shows the results.

Use the graph to find the half-life of the source.

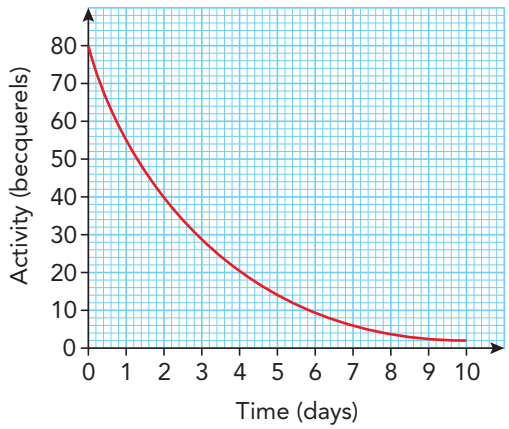

Figure P8.12: The count rate from a radioactive source is recorded for ten days.

Step 1: Calculate the count rate after one half-life.

The initial count rate is 80 count/s, so after one half-life it will have dropped to 40 count/s.

Step 2: Use the graph in Figure P8.13 to find the time taken for the count rate to drop to 40 count/s.

The half-life is two days.

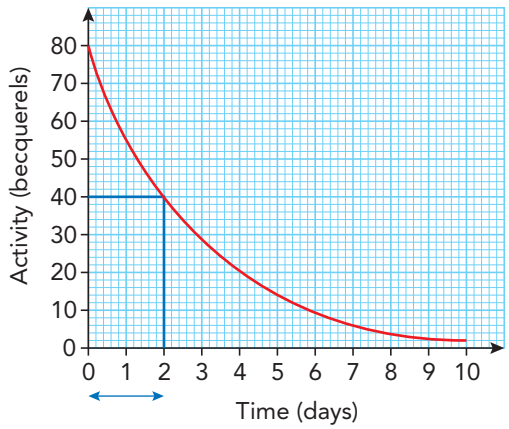

Figure P8.13: Use the graph to find the time taken for the count rate to drop to 40 count/s.

CONTINUED

Step 3: Check this by finding the time taken for the count rate to halve again, from 40 count/s to 20 count/s (Figure P8.14).

The count rate drops from 40 count/s to 20 count/s in two days, confirming that the half-life is two days.

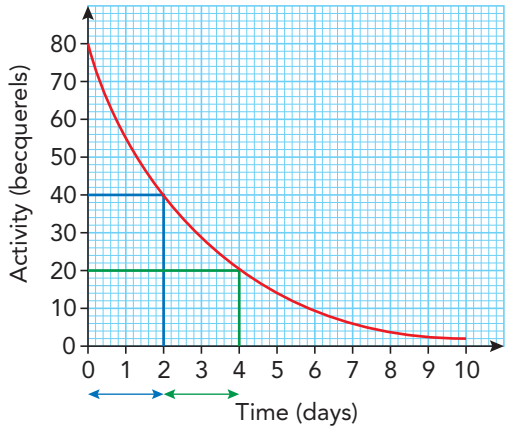

Figure P8.14: Use the graph to find the time taken for the count rate to halve again, from 40 count/s to 20 counts/s.

Answer

The half-life is two days.

WORKED EXAMPLE P8.04

Strontium-90 has a half-life of 28 years. A sample contains 480 unstable strontium-90 nuclei. How long will it take for the number of unstable nuclei to fall to 30?

Step 1: Draw a table like Table P8.06 to work out the number of half-lives for the number of unstable nuclei to drop to 30.

Number of half-lives	Number of unstable strontium-90 nuclei
0	480
1	240
2	120
3	60
4	30

Table P8.06: Radioactive decay data.

So, the number falls to 30 in four half-lives.

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CONTINUED

Step 2: Calculate how long this is in years.

One half-life is 28 years, so four half-lives:
$4 \times 28 = 112$ years.

Answer

112 years

Questions

P8.16 A sample of radioactive iodine contains 6400 undecayed atoms.

a How many will remain undecayed after three half-lives?

b The half-life of this isotope of iodine is eight days. How many atoms remain undecayed after 40 days?

P8.17 The half-life of thorium-227 is 19 days. How long will it take for the activity of the source to decrease by 75%?

P8.18 Figure P8.15 shows the count rate for a radioactive source at different times. What is the half-life of this source?

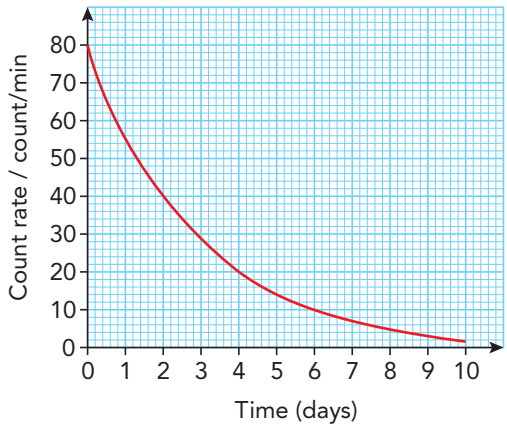

Figure P8.15: Count rate for a radioactive source at different times.

ACTIVITY P8.01

Modelling half-life

Radioactive decay is a random process. In this activity you will model radioactive decay using another random process – throwing dice or small cubes.

You will need a large number of dice – at least 100 – or small cubes with one side marked (as in Figure P8.16).

Figure P8.16: Using small cubes to model radioactive decay.

Place all the dice in a container, shake the container and throw the dice.

Any dice showing 6, or cube with the marked side facing upwards, has 'decayed'. Count how many have decayed.

Create a table like Table P8.07 and record your results.

Throw number (time)	Number decaying (activity)	Number remaining (*N*)

Table P8.07: Table for radioactive decay simulation.

Repeat until all the dice have decayed.

Draw two graphs, showing:

- activity against time
- number of 'nuclei' remaining against time.

Questions

1 What do you notice about the two graphs?

2 Calculate the half-life from each graph. What do you notice?

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CONTINUED

Peer assessment

Swap graphs with another student. Give them a tick for each of the following:

- a title which describes what the graph shows
- axes drawn with a pencil and ruler
- both axes labelled
- all points plotted correctly
- an appropriate curve drawn
- lines for determining half-life drawn with a ruler.

Dangers of radioactive materials

Effects of radioactivity on cells

There are three ways in which radiation can damage living cells.

- An intense dose of radiation causes a lot of ionisation in a cell, which can kill the cell. This is what happens when someone suffers radiation burns. The cells affected simply die, as if they had been burnt. If the sufferer is lucky and receives suitable treatment, the tissue may regrow.
- If the DNA in the cell nucleus is damaged, the mechanisms that control the cell may break down. The cell may divide uncontrollably, causing a tumour to form. This is how radiation can cause cancer.
- If the affected cell is a gamete (a sperm or egg cell), the damaged DNA of its genes may be passed on to future generations. This is how radiation can produce genetic mutations. Occasionally, a mutation can be beneficial to the offspring, but more often it is harmful. A fertilised egg cell may not develop at all, or the baby may have some form of genetic disorder.

Today, we know much more about radiation and the safe handling of radioactive substances. Knowing how to reduce the hazards of radiation means that we can learn to live safely with it and put it to many worthwhile purposes.

Safety precautions

Knowing about the radiation produced by radioactive materials helps us know how to handle them as safely as possible. Anyone working with, or being exposed to, ionising radiation must take safety precautions, such as shielding, or limiting their exposure time. Table P8.08 and Figure P8.17 show common safety precautions when dealing with radioactive material.

Figure P8.17: Common safety precautions when dealing with radioactive material.

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Safety precaution	Explanation
a Workers in contaminated areas wear protective suits	The suit will absorb radiation. Different materials can be used depending on the type of radiation. For γ-rays, lead-lined suits can be used.
b Radioactive hazard labels	These warn people of the danger so they can stay at a safe distance and reduce the time they are near the source. Labels must be used whenever radioactive materials are being transported.
c Photographic film dosimeter badges	These monitor the amount of exposure a person has had. Once the safe limit is reached, workers may be transferred to other areas.
d Remote operating of scanners	The operator usually controls the scanner from a separate area. This increases their distance from the source. They may also be behind a screen which will absorb some of the radiation.
e Storage boxes for sources	Radioactive sources must be stored securely, usually surrounded by lead to absorb most of the radiation. Schools are required to record how long radioactive sources are used for, and by whom. This allows them to ensure no one is exposed for too long.

Table P8.08: Safety precautions for dealing with radioactive material.

Question

P8.19 Figure P8.18 shows a radiation detection badge.

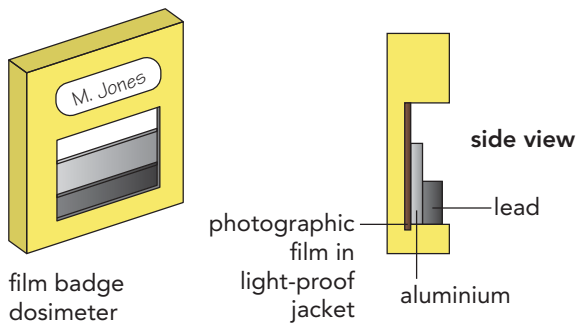

Figure P8.18: A radiation detection badge.

a What you would see if the film inside the badge was developed if the wearer had been exposed to:

i β-radiation?

ii γ-radiation?

b Why is the badge not suitable for detecting exposure to α-radiation?

Using radioactivity

Smoke detectors

These are often found in domestic kitchens, and in public buildings such as offices and hotels. If you open a smoke detector to replace the battery, you may see a yellow and black radiation hazard warning sign (Figure P8.19a). The radioactive material used is americium-241, a source of α-radiation. Figure P8.19b shows how the smoke detector works.

The americium source used in smoke detectors has a long half-life of about 430 years. This means that the count rate from the source will not drop significantly over the time the detector is in use.

a

b

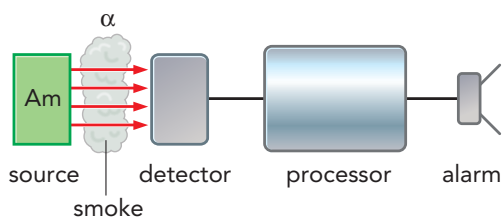

Figure P8.19 a: The inside of a smoke detector. The source of radiation is a small amount of americium-241. **b:** Block diagram of a smoke detector. The alarm sounds when smoke absorbs the α-radiation.

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- Radiation from the source falls on a detector. Since α-radiation is charged, a small current flows in the detector. The output from the processing circuit is off, so the alarm is silent.
- When smoke enters the gap between the source and the detector, it absorbs the α-radiation. Now no current flows in the detector, and the processing circuit switches on, sounding the alarm.

In this application, a source of α-radiation is chosen because α-radiation is easily absorbed by the smoke particles.

Food irradiation

This is a way of preserving food. Food often decays because of the action of microbes. These can be killed using intense γ-rays. Sterile foods have some particular uses: on space missions (where long-life is important) and for some hospital patients whose resistance to infection by microbes is very low. Figure P8.20 shows a display from the Nehru Science Centre in Mumbai which demonstrates the advantages of irradiating food.

Figure P8.20: The microbes which would cause decay have been killed by radiation in the top sample.

Sterilisation

Sterilisation of medical products works in the same way as food irradiation. Syringes, scalpels and other instruments are sealed in plastic bags, as shown in Figure P8.21, and then exposed to gamma radiation. Any microbes present are killed, so that, when the packaging is opened, the item is guaranteed to be sterile. γ-radiation is used because it can penetrate the plastic and can pass through the equipment, making sure all parts are sterilised.

Figure P8.21: The sealed package ensures the syringe remains sterile once γ-rays have killed all pathogens.

Thickness measurements

In industry, β-radiation is often used to measure thickness. Manufacturers of paper need to be sure that their product is of a uniform thickness. To do this, β-radiation is directed through the paper as it comes off the production line. A detector measures the amount of radiation getting through (Figure P8.22).

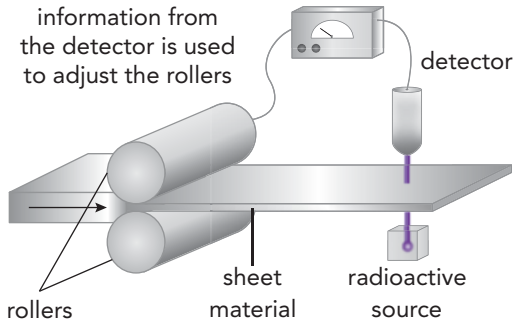

Figure P8.22: If the material gets too thick, less radiation will be detected. This will cause the rollers to be moved closer together, making the sheet thinner.

If the paper is too thick, the radiation level will be low and an automatic control system adjusts the thickness. The same technique is used in the manufacture of plastic sheeting and aluminium foil. β-radiation is used in this application because α-radiation would be absorbed entirely by the paper, plastic or aluminium.

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γ-radiation would hardly be affected, because it is the most penetrating.

Sheet steel factories use a similar system but with a γ–source.

Cancer diagnosis and treatment

Tracers

The diagnosis of some diseases, including cancers, may be carried out using a source of γ-radiation. The patient is injected with a radioactive chemical and a scanner is used to trace the path of the chemical. Figure P8.23 shows a scan of a patient with a kidney blockage. The tracer technetium-99 is injected into the patient's blood. The scan shows that the tracer is not passing through the kidney shown on the right as well as it is through the other kidney. This indicates that there is a blockage. The technetium isotope used has a relatively short half-life of about six hours. This is long enough for it to be used to trace the blockage, but it does not remain radioactive very long inside the patient's body.

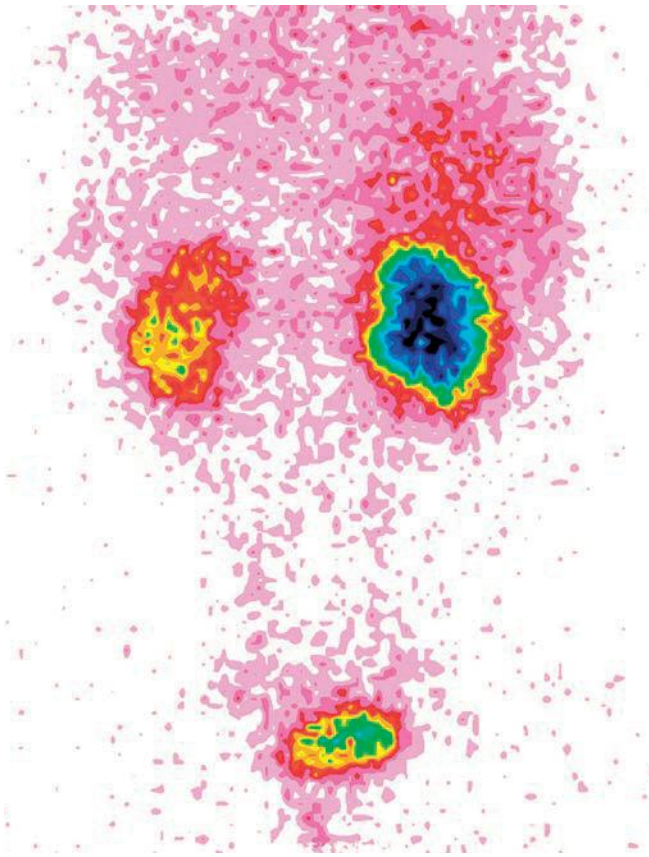

Figure P8.23: The tracer can be detected in both kidneys and the bladder. More γ-rays are detected from the kidney seen on the right, suggesting a problem there.

Radiotherapy

Radiation can cause cancerous tumours, but it can also be used to treat them. The patient shown in Figure P8.24 is receiving radiation as part of a treatment for cancer. A beam of γ-rays is directed at the tumour that needs to be destroyed. The source moves around the patient, always aiming at the tumour. In this way, other tissues receive only a small dose of radiation. Radiation therapy is often combined with chemotherapy (using drugs to target and kill the cancerous cells).

Figure P8.24: Radiation can cause cancer, but it can also be used in its cure. This patient is being exposed to γ-rays from a radioactive source.

Questions

P8.20 A smoke detector uses an α-source. Explain why:

- **a** a β- or γ-source would not work
- **b** it is safe to have this type of smoke detector in your home
- **c** the source used must have a half-life of years rather than days.

P8.21 Describe what would happen if the sheet shown in Figure P8.22 became too thin.

P8.22 When medical equipment is to be sterilised, it is first sealed in a plastic wrapper. Why does this not absorb the radiation used?

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PROJECT 8.01 DEMYSTIFYING RADIOACTIVITY

We have known about radioactivity for just over a century. In that time it has attracted a lot of sensational attention as an amazing cure-all, an invisible killer or for its fictional ability to mutate humans or animals into monsters.

Figure P8.25: This is the international warning sign for ionising radiation.

Over the last century we have learnt that, although dangerous, ionising radiation can be very useful and, if handled correctly, it can be safe (Figure P8.25).

Your task is to prepare a television segment or magazine article about radioactivity aimed at teenagers to explain the science of radioactivity and its uses and dangers.

You should:

- describe and illustrate the three types of radioactive emission
- explain how we can use knowledge about their penetrating power to use and store sources safely
- explain what is meant by half-life and why some radioactive waste must be stored securely for many years
- include as many practical examples of the uses of radioactivity as you can.

You should present your work as a video or a group presentation to the class, or in a written article.

Much of the fear which surrounds radioactive materials is made worse by the language surrounding it. Words such as 'mutation' and 'half-life' are not in everyday use and can add to the feeling that radiation is a weird scientific threat. To counter this, your presentation should include and explain the following key terms:

- radioactive
- α-particle
- β-particle
- γ-ray
- ionisation
- mutation
- radioactive isotope
- nuclear decay
- half-life
- background radiation.

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SUMMARY

The atom consists of a tiny positive nucleus surrounded by mainly empty space with negative electrons orbiting.
The nucleus contains two types of nucleons: positively charged protons and neutral neutrons.
Protons and electrons have equal but opposite charge.
A nucleus can be described using the notation ${}^{A}_{Z}X$, where X is the chemical symbol, Z the number of protons and A the number of nucleons.
Isotopes are nuclei of the same element which have the same proton number but different nucleon numbers.
Nuclear fission is the splitting of a large nucleus, which releases a lot of energy.
Nuclear fusion is joining together of small nuclei, which releases even more energy than fission.
We are surrounded by ionising background radiation from natural and man-made sources.
Unstable isotopes decay randomly.
Radioactive decay leads to three types of emissions: α-particles, β-particles and γ-rays.
α- and β-emissions change the nucleus to that of a different element.
α- and β-emissions can be described using balanced nuclide equations.
The half-life of a radioactive source is the time taken for half its radioactive nuclei to decay.
α-, β-, and γ-radiation can all ionise cells, leading to mutations and tumours. Safety precautions must be taken when using radioactive materials.
When used safely, radioactive materials have many uses, particularly in medicine and engineering.

PRACTICE QUESTIONS

1 A nucleus is represented by the notation ${}^{193}_{82}Pb$. **Identify** what particles it contains.

A 82 protons and 193 neutrons

B 82 protons, 82 electrons and 111 neutrons

C 82 neutrons and 111 protons

D 82 protons and 111 neutrons **[1]**

2 An element has two isotopes. Identify what is different for the two isotopes.

A the number of protons

B the chemical symbol

C the number of neutrons

D the chemical properties of the isotope **[1]**

3 **Give** *one* natural source of background radiation and *one* man-made source. **[2]**

4 Nuclear radiation can cause ionisation by knocking electrons out of atoms.

Give the *three* types of nuclear radiation in order of their ionising power, with the most ionising first. **[2]**

COMMAND WORD

identify: name/select/recognise.

COMMAND WORD

give: produce an answer from a given source or recall/memory.

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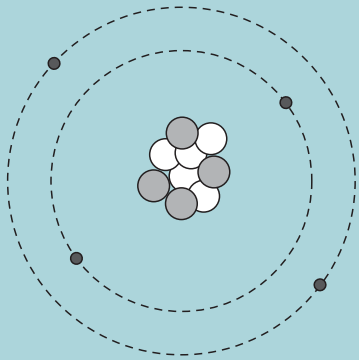
CONTINUED

5 A source contains 240 g of a radioactive isotope. The half-life of the source is three hours.

Calculate how much of the isotope will be left after 12 hours. **[1]**

6 The diagram shows a neutral beryllium atom.



a Identify how many protons it has. **[1]**

b Identify its nucleon number. **[1]**

c Identify how many neutrons it has. **[1]**

d Copy and complete this nuclide notation to represent the beryllium nucleus: **[1]**

$^{\square}_{\square}$Be

e A radioactive isotope of beryllium is known as beryllium-11.

Deduce the number of protons and neutrons in the nucleus of this isotope. **[2]**

f Give the nuclide notation for beryllium-11. **[1]**

[Total: 7]

7 A radioisotope of radium has a half-life of 1600 years.

a **Define** *half-life*. **[1]**

b The paint in a luminous watch face contains 20 mg of the radioisotope of radium.

Calculate the mass that remains undecayed after 3200 years. **[1]**

c Radium emits ionising radiation.

State how this can affect living cells. **[1]**

d **Describe** the safety precautions which must be taken when radioactive radium is used in a school laboratory. **[2]**

[Total: 5]

8 α-particles are a type of ionising nuclear radiation.

a Describe the structure of an α-particle. **[1]**

b Scientists test a rock with a Geiger counter and find that it is emitting radiation.

They suspect it is α-radiation. **Suggest** how they could test to confirm this. **[2]**

c Copy and complete the following nuclear equation to show how emitting an α-particle changes a uranium isotope.

$^{238}_{92}\text{U} \rightarrow {}^{234}_{\square}\text{Th} + {}^{\square}_{\square}\alpha$ **[3]**

[Total: 6]

COMMAND WORD

calculate: work out from given facts, figures or information.

COMMAND WORDS

deduce: conclude from available information.

define: give a precise meaning.

state: express in clear terms.

describe: state the points of a topic/give characteristics and main features.

COMMAND WORD

suggest: apply knowledge and understanding to situations where there are a range of valid responses in order to make proposals/put forward considerations.

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SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
name the particles in the nucleus and state their charge	P8.01			
define proton number Z	P8.01			
define nucleon number A	P8.01			
describe nuclei using the notation ${}^{A}_{Z}\mathrm{X}$	P8.01			
describe the similarities and differences between two isotopes of an element	P8.01			
describe the processes of nuclear fission and fusion	P8.01			
state what the proton number tells us about the charge of a nucleus	P8.01			
recall the main sources of background radiation	P8.02			
state the units of count rate	P8.02			
explain what it means to say radioactive emission is random	P8.02			
describe the nature, ionising effect and penetration of α-, β- and γ-radiation	P8.02			
describe how ionising radiation can be detected	P8.02			
state that some isotopes are radioactive and decay to become different elements	P8.02			
describe how α- and β-emissions change nuclei, using nuclide equations	P8.02			
define the half-life of a radioactive source and use it in calculations	P8.02			
describe the effects of ionising radiation on living cells, and the safety precautions which should be taken when using radioactive materials	P8.02			
describe and explain practical uses of radioactive materials.	P8.02			

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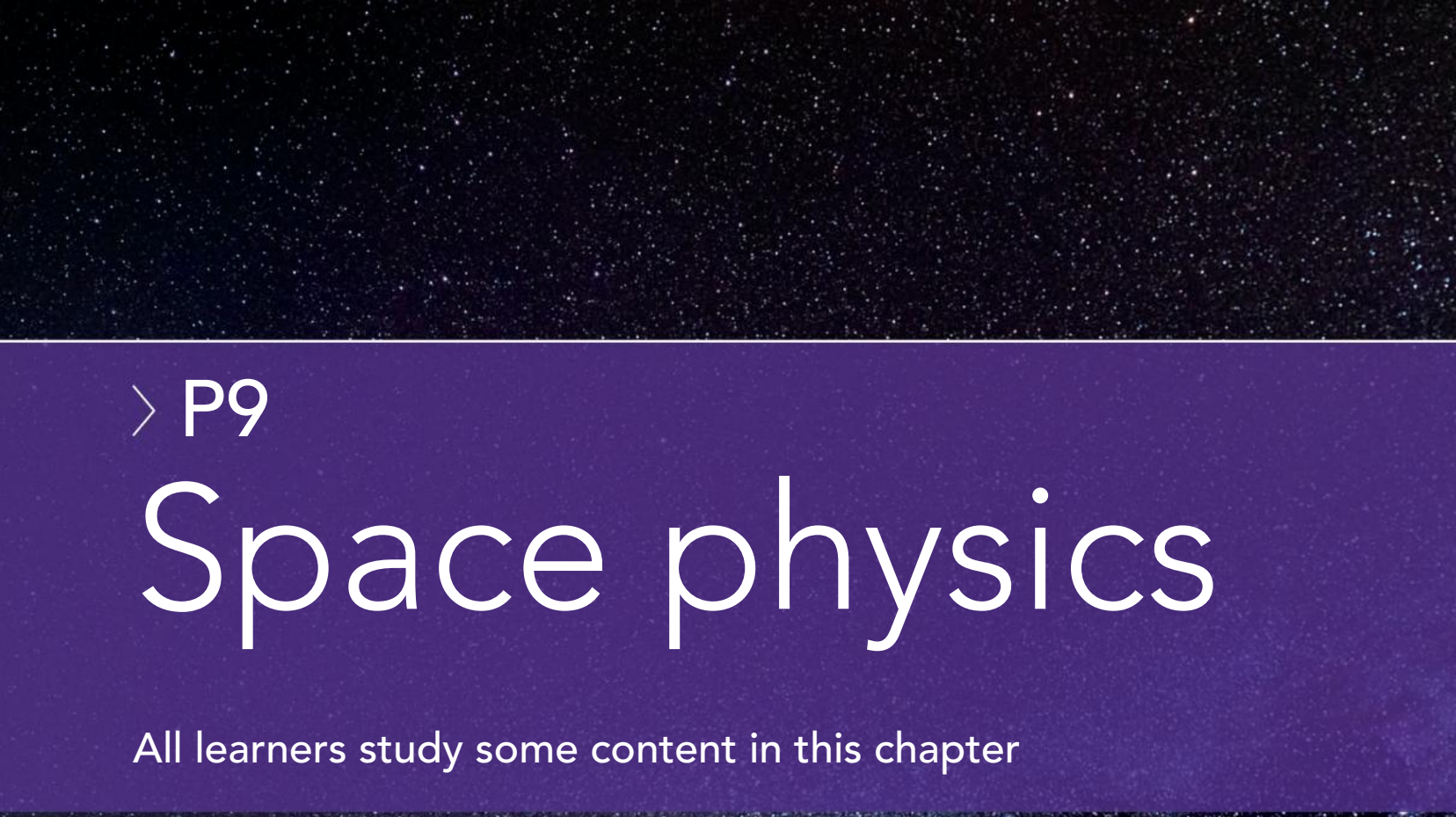

P9

Space physics

All learners study some content in this chapter

IN THIS CHAPTER YOU WILL:

- describe the main constituents of the Solar System
- calculate the time light takes to travel from the Sun to the planets
- explain the movement of bodies in the Solar System in terms of gravitational attraction
- describe and calculate orbital speed
- describe the Sun and galaxies, including the Milky Way
- describe how stable stars (such as the Sun) are powered by the thermonuclear fusion of hydrogen
- describe the life cycle of stars like our Sun and more massive stars
- learn about the relative separation of planets, stars and galaxies
- describe the Big Bang theory.

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BEFORE YOU START

Spend two minutes thinking about these questions before comparing notes with your neighbour for a further two minutes, adding to or correcting your own work. Be prepared to share your thoughts with the class.

- List the differences between planets and stars.
- Where does the Sun get its energy?
- What colour are stars?
- What is a galaxy and what is the name of our galaxy?
- List what you know about the Universe.

SCIENCE IN CONTEXT P9.01

How many planets?

Humans have known about the first five planets, Mercury, Venus, Earth, Mars and Jupiter, for a long time as we can see them with the naked eye. In 1610, the newly invented telescope allowed Galileo Galilei to discover Saturn. Uranus was added by William Herschel in 1781. Careful observations of the orbit of Uranus showed it did not follow a smooth orbital path as the other planets did. Astronomers predicted this was due to the effect of the gravitational pull of another planet. They calculated where this should be and found Neptune in 1846. Tiny, distant Pluto was discovered in 1930, bringing the total to nine planets. And so it remained until 2006.

In the 1990s, several objects with similar mass to Pluto were discovered. This created a problem. Should these be named as planets, and if not, could Pluto still be classed as a planet? The International Astronomical Union decided a new definition for the title planet was needed. It came up with three rules. To be a planet, a body must:

- orbit the star (our Sun)
- have enough mass that its gravity pulls it into a spherical shape
- have a large enough gravitational pull to clear away any other objects of a similar size near its orbit around the Sun.

Pluto failed the third rule due to the discovery of an object named Eris, about the size of Pluto, orbiting close to Pluto. Pluto and Eris were both reclassified as dwarf planets, leaving a total of eight planets (Figure P9.01).

Discussion questions

1 Why is it important to have international agreement about the definition of a planet? Are there any other areas where scientists have agreed standard definitions?

2 A lot of people felt that Pluto should have kept its status as a planet. What consequences would this have had?

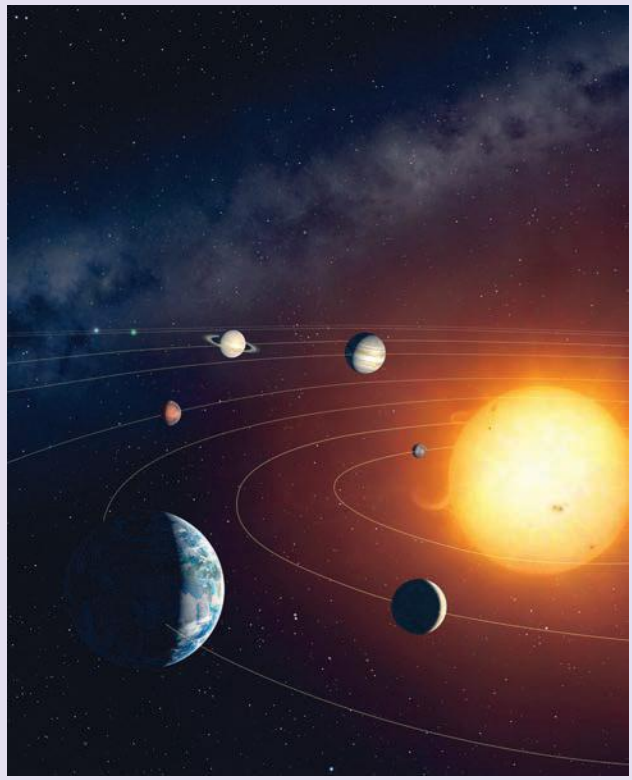

Figure P9.01: This artist's impression shows the Sun and the eight planets we now know orbit the Sun.

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P9.01 The Solar System

The Solar System consists of the Sun, which is our star, and all the objects which orbit it (Figure P9.02). It includes the following:

- There are eight **planets**: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus and Neptune.
- There are **minor planets**, such as Pluto and Eris. In 2014, the International Astronomical Union recognised five dwarf planets, but it is believed there are more than 200 in all.
- Moons that orbit planets and dwarf planets.
- Millions of **asteroids**: these are rocky objects which are smaller than planets (Figure P9.03). Most asteroids are found in the asteroid belt between the orbits of Mars and Jupiter.

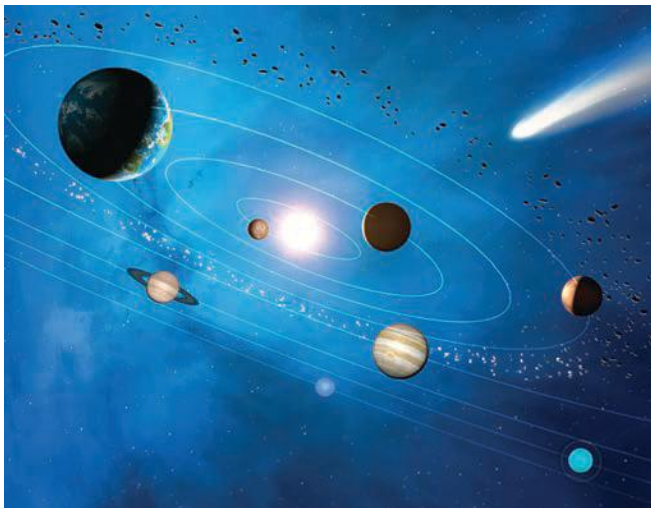

Figure P9.02: An artist's impression of the Solar System with a visiting comet. The picture is not to scale.

KEY WORDS

planet: large spherical object that orbits the Sun without another similar object close to it.

minor planet: an object which orbits the Sun but is not large enough or far enough from another object to be defined as a planet.

asteroid: lump of rock which orbits the Sun.

Figure P9.03: It is believed that the dinosaurs became extinct due to a large asteroid hitting the Earth, creating a huge crater and throwing up so much dust that the Sun's rays could not reach Earth for more than a year.

P9.02 The Sun as a star

The Sun is the closest star to the Earth and so it appears large in our sky. However, it is a medium size star when compared to other stars. The Sun is made up of about 75% hydrogen and about 24% helium. The rest (about 1%) is made up of other elements, such as oxygen and carbon.

The glowing hydrogen at the surface of the Sun radiates energy. About 40% of this energy is visible light, about 50% is infrared radiation, and the remaining 10% is ultraviolet. Earth's atmosphere absorbs a lot of this ultraviolet radiation. The ozone layer, in particular, absorbs most of the harmful (more ionising) ultraviolet.

The Earth orbits the Sun at a distance of about 150 million kilometres, which is within the habitable zone. This is the zone where water can exist in liquid form (an essential requirement for life as we know it). If it was hotter, the water vapour would never condense; if it was colder, ice would never melt.

The Sun contains over 99.86% of the mass of the Solar System, so it exerts a big gravitational force on the planets and causes them to follow nearly circular orbits.

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Stars are powered by nuclear reactions that release energy. **Stable stars** like our Sun are powered by the nuclear fusion (or thermonuclear fusion) of hydrogen into helium. This makes the Sun shine. It is so hot inside the Sun that matter exists as **plasma** (positive ions and electrons). Although the Sun produces gamma rays because of the nuclear fusion process, collisions with the plasma mean that it takes about 100 000 years for that energy to reach the Sun's surface. In addition, because the energy is spread over a big surface (called the photosphere) the temperature is lower at the Sun's surface (about 5800 K compared to a core temperature of about 15 000 000 K).

Questions

P9.01 From which two elements is the Sun mostly made?

P9.02 Imagine that Earth orbits a star that gives off most of its energy in the ultraviolet region of the spectrum. Discuss whether our eyes would still have evolved to see visible light.

P9.03 Name the process that makes stable stars, such as our Sun, shine.

Distances in space

When you look into the night sky, the light that you see from the stars has been travelling for many years. Astronomers use this idea as a way of measuring vast distances. A **light-year** is a measure of distance (not time). It is the distance that light travels through space in one year. Light travels at a constant speed of 3×10^8 m/s through a vacuum. This means that the time it takes to travel somewhere is directly proportional to distance.

One light-year is the distance that light travels in one year.

$$\text{distance} = \text{speed} \times \text{time}$$

So, one light-year = 3×10^8 m/s × 365.25 days × 24 hours × 3600 seconds = 9.5×10^{15} m.

KEY WORDS

stable star: a star that is not collapsing or expanding because the inward force of gravity is balanced by radiation pressure, which pushes outwards.

plasma: a completely ionised gas in which the temperature is too high for neutral atoms to exist so it consists of electrons and positively-charged atomic nuclei.

light-year: the distance travelled in space by light in one year (it is equivalent to about 9.5×10^{15} m).

The distance between stars is much bigger than the size of each solar system. After the Sun, our next nearest star is Proxima Centauri, which is about 4.2 light-years away. When you see Proxima Centauri, the light left it 4.2 years ago; sunlight only takes eight minutes to reach us because the Sun is much closer to us. Pluto has an elliptical orbit but, on average, it is 40 times further from the Sun than the Earth is. But this is dwarfed by the distance between Proxima Centauri and the Sun, which is 7000 times further from the Sun than Pluto is.

Questions

P9.04 The Sun is about eight light-minutes away. It takes sunlight about eight minutes to reach Earth on its journey from the Sun.

- **a** Given that the speed of light is 3×10^8 m/s, how far away is the Sun in kilometres?
- **b** How many years would it take a car to get to the Sun travelling at 120 km/h?

P9.05 After our Sun, Proxima Centauri is our next nearest star. It is about 4.2 light-years away.

- **a** How many seconds does it take light from Proxima Centauri to reach Earth?
- **b** How far away is Proxima Centauri in km?
- **c** Helios I & II hold the record as the fastest ever space probes at 252 738 km/h (about 70 km/s).

  How many years would it take these space probes to reach Proxima Centauri?
- **d** How long would it take them to reach the nearest galaxy 25 000 light-years away from us?

The Sun's gravitational pull

The Sun is at the centre of the Solar System. It is by far the most massive object in the Solar System and makes up about 99.8% of the mass of the Solar System. As gravitational attraction depends on mass, the gravitational field strength of the Sun is far larger than the field of any other object in the Solar System.

The planets, minor planets, asteroids and meteoroids and comets all orbit the Sun. They are held in orbit by the gravitational attraction of the Sun.

Orbital speed

The speed of a planet in orbit round a star is called its orbital speed (v). As the planets' orbits are almost circular, the distance they travel can be calculated if we know the

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average **orbital radius**, which is the average distance of the planet from the Sun, or the average radius of the orbit (Figure P9.04).

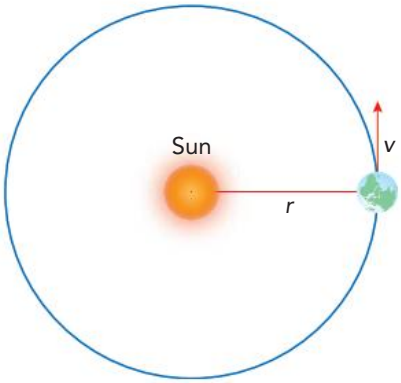

Figure P9.04: To calculate the orbital speed, we assume that the orbits are circular.

The distance travelled by the planet is the circumference of its orbit. The circumference of a circle is equal to $2\pi r$.

If we also know the time for the planet to orbit the Sun – known as its **orbital period** (T) – we can calculate the speed:

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

So, the average orbital speed, v, can be calculated from its orbital period, T, and its average orbital radius r, using the equation:

KEY EQUATION

$$\text{average orbital speed} = \frac{2 \times \pi \times \text{orbital radius}}{\text{orbital period}}$$

$$v = \frac{2\pi r}{T}$$

KEY WORDS

orbital radius: the average distance of the planet from the Sun.

orbital period: the time taken for a planet to complete one full orbit of the Sun.

WORKED EXAMPLE P9.01

Calculate the orbital speed of Earth.

Step 1: Write down what you know:

$r = 150\,000\,000\,\text{km}$

$T = 1$ year

Step 2: Convert T to seconds.

1 year = 1 × 365.25 = 365 days

365.25 days = 365.25 × 24 = 8766 hours

8766 hours = 8766 × 60 × 60

= 31 557 600 seconds

Step 3: Substitute values for T and r into the equation and calculate v.

$$v = \frac{2\pi r}{T}$$

$$= \frac{2\pi \times 150\,000\,000\,\text{km}}{31\,557\,600\,\text{s}}$$

$$= 29.85\,\text{km/s}$$

Answer

29.85 km/s

Like other non-contact forces such as magnetism and static electricity, gravitational attraction decreases with distance. This means that the outer planets experience less gravitational force from the Sun than the inner planets do. Table P9.01 shows that the orbital speed of a star also decreases with the distance from the Sun.

Planet	Average orbital radius / million km	Orbital period / years	Orbital speed / km/s
Mercury	58	0.2	47.9
Venus	108	0.6	35.0
Earth	150	1	29.8
Mars	228	1.9	24.1
Jupiter	778	12	13.1
Saturn	1427	30	9.7
Uranus	2870	84	6.8
Neptune	4497	165	5.4

Table P9.01: The orbital speed of a star decreases with the distance from the Sun.

Question

P9.06 Calculate the orbital speed of the minor planet Pluto which has an orbital radius of 5900 million km and an orbital period of 248 years. Does this fit the same pattern as the planets?

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P9.03 The life cycle of stars

The possible life cycles of stars are summarised in Figure P9.05. Every star begins as a **protostar** but the future path of a star is determined by its mass.

How a star is born

A protostar is the first step in star formation. Stars form from **interstellar clouds** of gas and dust.

As the force of gravity pulls the gas molecules closer together, their gravitational potential energy is transferred to kinetic energy. As the molecules collide, their kinetic energy is transferred into thermal energy. The clump contracts into a spinning sphere of super-hot gas known as a protostar. A protostar continues to grow by pulling in more material from the molecular cloud.

As the star forms, nuclear reactions happen within it, causing outward forces which balance the inward force of gravity. When this happens, the star is described as stable. Our Sun is 4.6 billion years old and is half-way through its time as a stable star.

When the fuel for the nuclear reactions starts to run out, the star will come to the end of its life cycle. What happens depends on the mass of the star.

Small mass stars

Our Sun has a relatively small mass. When a small star comes to the end of its stable period it cools and swells up, forming a **red giant**. When our Sun expands, it will swallow up Mercury and Venus. The star then collapses in on itself to form a **white dwarf** star. The outer layers are blown away to form a **planetary nebula** (Figure P9.06).

KEY WORDS

protostar: a very young star that is still gathering mass from its parent molecular cloud.

interstellar cloud: a cloud of gas and dust that occupies the space between stars.

red giant: a star that began with fewer than eight solar masses and is burning helium in its core; its shell of hydrogen has expanded and cooled.

white dwarf: the final stage of a star that started with fewer than eight solar masses after all its fuel has been used up.

planetary nebula: a bubble of gas surrounding a white dwarf star that used to be the outer shell of a red giant from which it collapsed.

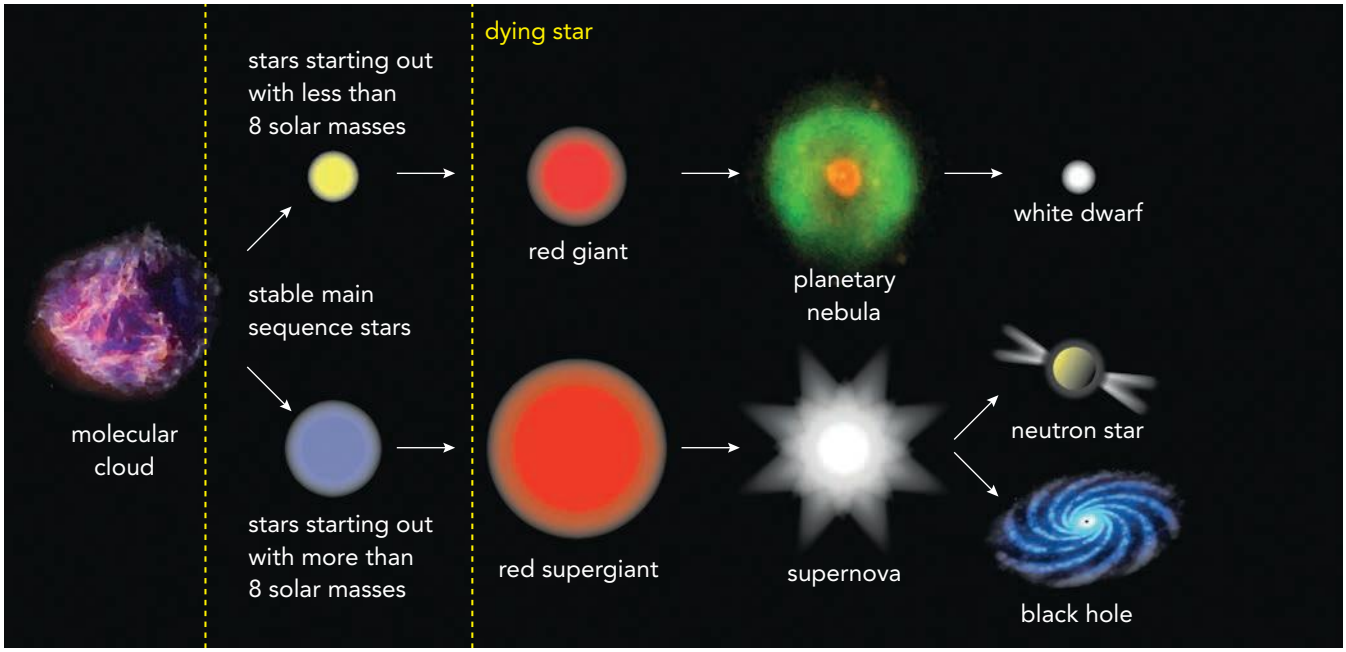

Figure P9.05: The life cycle of a star depends on its initial (starting) mass. All stars begin as protostars in molecular clouds before joining the main sequence. Stars with a starting mass of fewer than eight solar masses follow the top row. Heavier stars move along the bottom row and explode as supernovae. After the supernova stage, the lighter stars become neutron stars while the rest become black holes.

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Figure P9.06: The planetary nebula NGC 6543, known as the Cat's Eye Nebula, taken from the Hubble Space Telescope. The white dot in the middle is a white dwarf star, which is what our Sun will become in about 5 billion years.

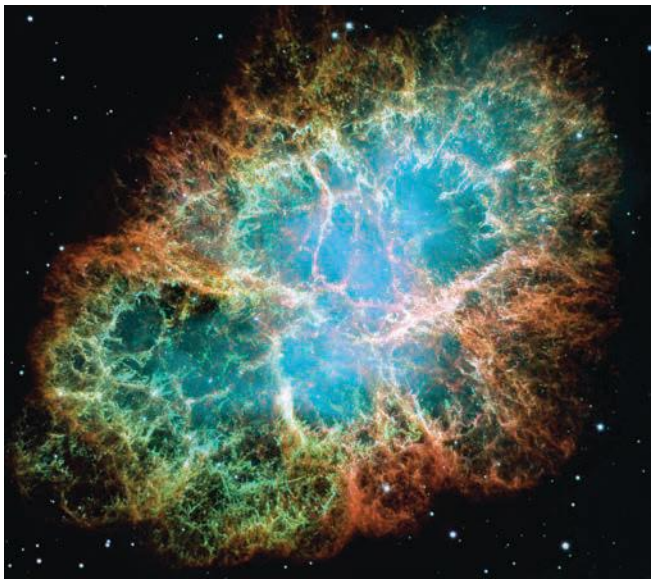

Figure P9.07: A supernova in 1054 left behind the Crab Nebula and a neutron star somewhere within.

Larger stars

Larger stars also expand as they reach their end, swelling up to form a **red supergiant**. This eventually collapses and its outer layers are blown off in a huge explosion called a **supernova** (see Figure P9.07).

The core of a supernova forms a very dense object. Again, what happens depends on the mass of the star.

- A large mass star leads to the formation of a **neutron star**.
- A very large mass star may become a **black hole** – the most dense object in the Universe.

KEY WORDS

red supergiant: similar to red giants, they form when stars with at least eight times the mass of the Sun run out of hydrogen fuel in their core but fusion of hydrogen continues in the outer shells.

supernova: an exploding star that began life with more than eight solar masses and has run out of fuel.

neutron star: a collapsed star composed almost entirely of neutrons which forms when a star with more than eight solar masses reaches the end of its life.

black hole: the final stage in the life cycle of a star that started with more than eight solar masses; it has enough mass left over after exploding as a supernova to collapse to a point where gravity is so strong that not even light can escape.

Cosmic recycling

The nebula formed from a supernova explosion may lead to the formation of protostars, and in turn new stars with orbiting planets. This process can be repeated many times. Our own Sun is a third generation star, which means it includes matter that has been through two previous stars, including one which ended in a supernova explosion.

The intense heat of a supernova explosion is the only place where the heavier chemical elements can form. These elements are present on Earth, including in our bodies. You have atoms in your body which originated in a long dead star.

Questions

P9.07
- **a** Explain how stars are formed.
- **b** What causes the centre of a star to warm up when it forms?

P9.08 Explain the following terms about the life cycle of a star:
- **a** protostar
- **b** red giant
- **c** white dwarf
- **d** supernova
- **e** neutron star
- **f** black hole.

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P9.09 Construct a flow chart to show how the stages listed in Question P9.08 fit together in the life cycle of stars.

P9.10 **a** Explain what is meant by nuclear fusion.

b Why can nuclear fusion only occur at high temperatures?

P9.04 Galaxies and the Universe

The force of gravity pulls stars together in groups called galaxies. The distances between stars in a galaxy is much greater than the distance between a star and its planets. Our Sun is one of many billions of stars in our galaxy, the Milky Way. The Milky Way is a spiral galaxy with a central bulge (see Figure P9.08). It has a diameter of 100 000 light-years. It is estimated that there are 200 billion (2×10^{11}) stars in the Milky Way.

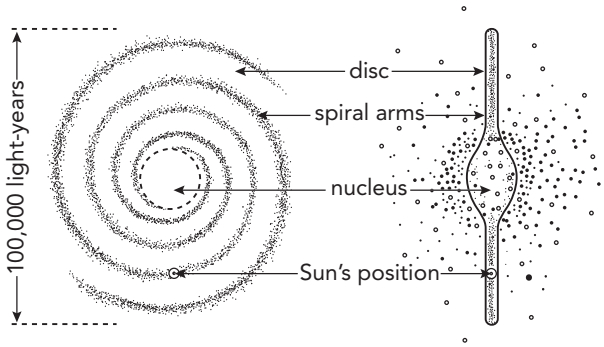

Figure P9.08: A schematic diagram of the Milky Way Galaxy. Our Solar System is located about 30 000 light-years from the galactic centre, two-thirds of the way along a spiral arm.

The Milky Way is one of many billions of galaxies that make up the Universe. Figure P9.09 shows an image of a galaxy with a structure similar to the Milky Way.

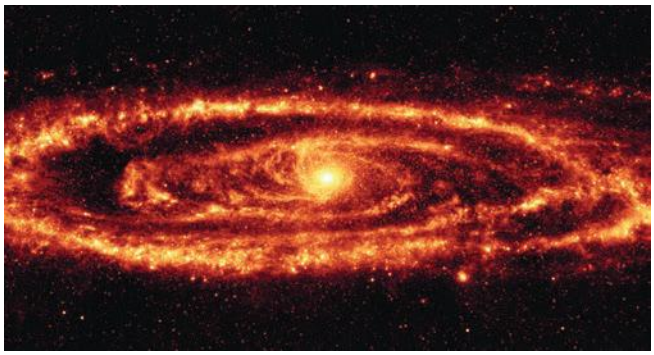

Figure P9.09: An infrared image of the Andromeda Galaxy, our closest spiral galaxy.

Questions

P9.11 How can the Canis Major Dwarf Galaxy be closer to us than we are to the centre of our own galaxy?

P9.12 Assuming that the average mass of a star is equal to the mass of the Sun (2×10^{30} kg), what is the mass of the Milky Way?

ACTIVITY P9.01

Talking about space

Working in pairs, take turns to speak or write a sentence using one of the following:

Earth, Sun, star, galaxy, red giant, red supergiant, white dwarf, black hole, supernova, Milky Way, neutron star, protostar, asteroid.

Peer assessment

Award your partner 1 mark for a simple correct statement, for example, 'The Earth is a planet'. If their sentence gives extra information relating to the chosen word, for example, 'The Earth is a planet which orbits the Sun', award 2 marks.

Think about the words you found difficult and discuss how you can improve your understanding.

The Big Bang Theory

You may have noticed that when an ambulance or police car goes past, the pitch of its siren seems to get lower as it moves away. The frequency appears to decrease as it moves away. Astronomers have noticed a similar phenomenon with light from different galaxies. Light from the galaxies seems to have a lower frequency than expected (this is known as red-shift). This suggests that the stars are all moving away from us. The effect is strongest in the furthest away galaxies, suggesting that these galaxies are moving away fastest.

These observations led to the development of the Big Bang Theory. This explains the observed movement of the galaxies using the idea that the entire mass of the Universe was compressed at one hot, dense point, and suddenly and rapidly expanded, and continues to expand.

The Big Bang Theory explains the observed movement of the galaxies. It also predicted that we should be able to detect radiation, known as cosmic microwave background radiation, left over from the original Big Bang (more accurately described as a rapid expansion). This was discovered in 1964 (see Figure P9.10) and provided evidence in support of the Big Bang Theory as well as helping to determine the age of the Universe.

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Figure P9.10: Robert Wilson and Arno Penzias in front of the radio telescope that detected the cosmic microwave background radiation.

There is still much to be discovered about the origins of the Universe. Although it remains a theory, the Big Bang Theory explains many of the observations astronomers have made. The Big Bang Theory states that:

- The mass of the Universe was compressed into a single point which had extremely high density and temperature.
- The Universe expanded rapidly from this point and continues to expand.
- The Universe is approximately 13.8 billion years old.

PROJECT P9.01 ARE WE ALONE IN THE UNIVERSE?

The possibility of life elsewhere in the Universe fascinates and frightens people in equal measure and is the subject of many science fiction stories, both in books and movies. Science fiction (as opposed to fantasy) often works better if the underlying science is correct or, at least, possible.

When looking for life beyond Earth, it is important to consider what conditions are required for life on Earth. We need liquid water (as a solvent for the chemical reactions needed for life), a source of energy (we depend on sunlight), and chemical building blocks. Scientists have discovered that most stars have solar systems of orbiting planets, increasing the chances that the conditions for life on Earth exist on other planets, beyond the Solar System.

However, liquid water is not the only possible solvent for chemical reactions. Ammonia and liquid hydrocarbons (like methane) are alternatives and have raised hopes of finding life on Titan, the largest moon orbiting Saturn.

Sunlight is not the only source of energy. In 1977, hydrothermal vents (called black smokers) were discovered at mid-ocean ridges several kilometres below the ocean surface. Even though they are far deeper than light can reach, ecosystems have formed around them. These ecosystems get their energy from the chemical reaction between oxygen and hydrogen sulfide. This has increased hopes of finding life beneath the ice of Europa, one of Jupiter's moons. Microbes have also been discovered deep underground in the Earth's crust.

Life on Earth is based on carbon, which can bond with up to four other atoms and forms more compounds than all other elements combined. However, life could also be based on silicon, which is in the same group in the Periodic Table and can also form a huge variety of compounds.

You have two tasks.

1 Use the internet to find more information on one of the following:
   - The search for Earth-like extrasolar planets (planets in other solar systems that match the conditions required for life on Earth): you will find there are many other requirements for more complicated life forms (for example, the spin of the planet has to be stable). You can probably think of more before going online.
   - The search for life within our Solar System: you could look at, for example, Mars, Europa or Titan.

2 Use the information presented here or the information you have found on the internet to complete a short piece of creative science fiction writing, based on scientific fact. Aim for a maximum of 800 words (or what your teacher suggests). Use your imagination, but make sure that your story is concise and the science is clear and correct.

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SUMMARY

The Sun is orbited by eight planets, minor planets, moons and asteroids.
All objects orbiting the Sun are kept in orbit by its gravitational attraction.
Light from the Sun takes approximately eight minutes to reach the Earth. The distances for sunlight to reach other planets can be calculated using the equation $\text{speed} = \frac{\text{distance}}{\text{time}}$
The Sun contains almost all of the mass of the Solar System and so has a very strong gravitational field.
The speed of an object in orbit can be calculated using the equation $v = \frac{2\pi r}{T}$ where r is the radius of the orbit and T is the orbital duration.
As distance from the Sun increases, its gravitational field strength decreases and the orbital speed of any orbiting object decreases.
Our Sun is an average star and is made mainly of hydrogen and helium.
Stable stars shine because of the thermonuclear fusion of hydrogen.
The Sun gives out most of its energy as infrared, visible and ultraviolet electromagnetic radiation.
A light-year is the distance that light travels in one year.
A light-year is defined as 9.5×10^{15} metres.
The Sun is one of many billions of stars in our Milky Way galaxy.
Our Milky Way galaxy is one of billions of galaxies in the Universe.
Our nearest galaxy is more than 25 000 light-years from Earth. So, galaxies are much further apart than stars, and stars are much further apart than planets.
All stars begin as protostars caused by the collapse of interstellar gas clouds.
A low mass star (less than eight times the mass of the Sun) swells into a red giant then becomes a white dwarf star and a planetary nebula.
A high mass star (more than eight times the mass of the Sun) explodes as a supernova then collapses to become a neutron star or, if it has a bigger mass, a black hole.
A supernova explosion creates elements heavier than iron and sends this material into the interstellar medium as a nebula that forms the raw material for new stars and solar systems.
The fact that galaxies are moving away from us suggests that the Universe is expanding and supports the Big Bang Theory.
The Big Bang Theory states that the Universe expanded rapidly from a tiny, hot, dense point 13.8 billion years ago, and that it continues to expand.

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PRACTICE QUESTIONS

1 **Identify** the force that keeps the planets in orbit round the Sun.

A momentum **B** air resistance **C** tension **D** gravity [1]

2 Identify the reason why stars shine.

A They are burning.

B Nuclear fusion is taking place inside the star.

C They are made of hot gases that are heated up when they collapsed from gas clouds.

D They are made of ether. [1]

3 Space scientists often use the unit called a light-year.

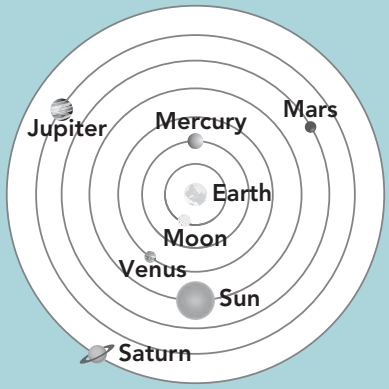
a **State** the quantity for which a light-year is the unit. [1]

b **Define** a light-year. [1]

c **Explain** why the light-year is a suitable unit for use in space physics. [1]

[Total: 3]

4 The diagram shows how people 1000 years ago thought the Solar System looked.



a State *one* way in which this model is different from what we now know about the Solar System. [1]

b State *one* way in which this model is similar to what we now know about the Solar System. [1]

c Mars is 228 million km from the Sun. **Calculate** the time it takes for light to travel from the Sun to Mars. The speed of light is 3×10^8 m/s. [3]

[Total: 5]

5 **a** **Give** the name that scientists use to describe a large group of stars. [1]

b State the force that holds these large groups of stars together. [1]

c Give the name of the large group of stars that includes our Solar System. [1]

[Total: 3]

6 **Describe** the life cycle of the Sun from how it formed until the point at which it runs out of fuel. [5]

COMMAND WORDS

identify: name/select/recognise.

state: express in clear terms.

define: give a precise meaning.

explain: set out purposes or reasons/make the relationships between things clear/say why and/or how and support with relevant evidence.

COMMAND WORDS

calculate: work out from given facts, figures or information.

give: produce an answer from a given source or recall/memory.

describe: state the points of a topic/give characteristics and main features.

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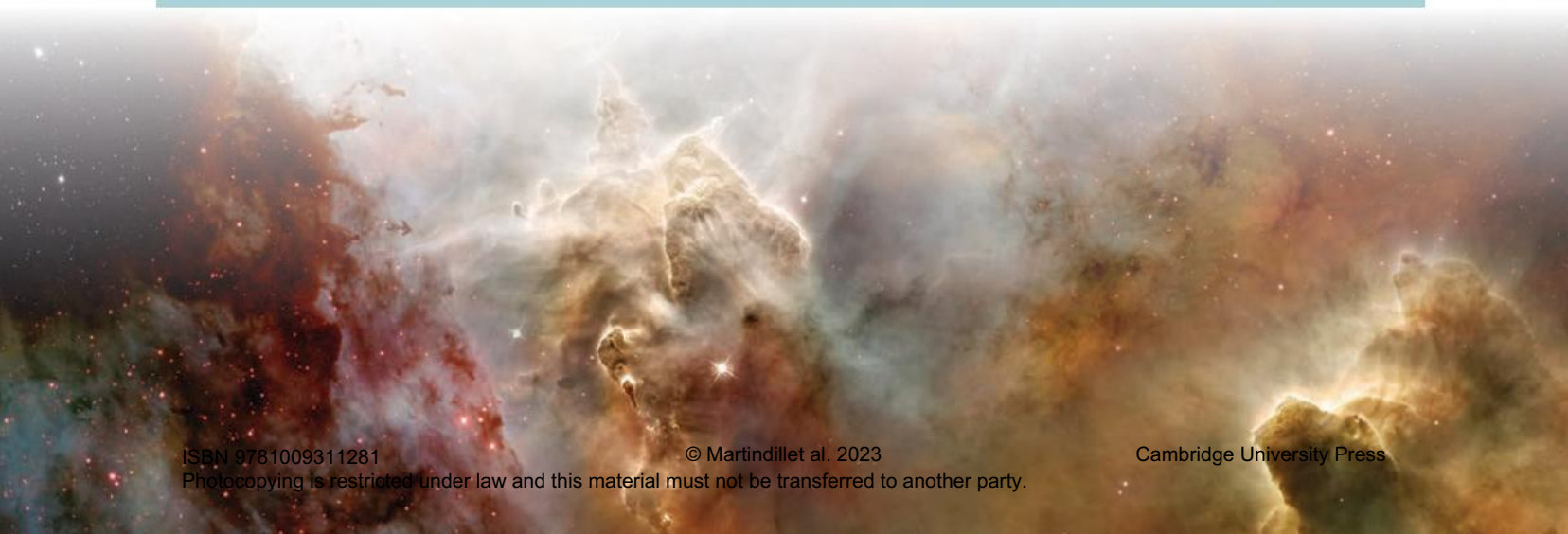
SELF-EVALUATION CHECKLIST

After studying this chapter, think about how confident you are with the different topics. This will help you to see any gaps in your knowledge and help you to learn more effectively.

I can	See topic . . .	Needs more work	Almost there	Confident to move on
name the different objects which orbit the Sun	P9.01			
calculate the time it takes for light to travel from the Sun to a given planet	P9.02			
name the force which keeps the planets in orbit	P9.02			
calculate orbital speed using the equation $v = \frac{2\pi r}{T}$	P9.02			
explain why the Sun has the largest gravitational field of any object in the Solar System	P9.02			
describe what the Sun is made of	P9.02			
recall what parts of the electromagnetic spectrum are emitted by the Sun	P9.02			
describe what powers a stable star	P9.02			
recall what a light-year is	P9.02			
describe how a protostar is formed and how it becomes a stable star	P9.03			
describe the life cycle of a star like the Sun, including the names of the different stages	P9.03			
describe the life cycle of stars exceeding eight solar masses, including the names of the different stages	P9.03			
describe the role of supernovae in the formation of new stars	P9.03			
describe the composition of the Milky Way galaxy	P9.04			
state the three things the Big Bang Theory tells us about the Universe.	P9.04			



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Glossary

Command words

calculate: work out from given facts, figures or information.

comment: give an informed opinion.

compare: identify/comment on similarities and/or differences.

consider: review and respond to given information.

contrast: identify/comment on differences.

deduce: conclude from available information.

define: give a precise meaning.

describe: state the points of a topic/give characteristics and main features.

determine: establish an answer using the information available.

discuss: write about issue(s) or topic(s) in depth in a structured way.

evaluate: judge or calculate the quality, importance, amount or value of something.

examine: investigate closely, in detail.

explain: set out purposes or reasons/make the relationships between things clear/say why and/or how and support with relevant evidence.

give: produce an answer from a given source or recall/memory

identify: name/select/recognise.

justify: support a case with evidence/argument.

outline: set out the main points

predict: suggest what may happen based on available information.

show (that): provide structured evidence that leads to a given result.

sketch: make a simple freehand drawing showing the key features, taking care over proportions.

state: express in clear terms.

suggest: apply knowledge and understanding to situations where there is a range of valid responses in order to make proposals/put forward considerations.

Key words

Biology

absorbed: soaked up; nutrients are absorbed from the alimentary canal into the blood, through the walls of the small intestine.

absorption: the movement of nutrients from the alimentary canal into the blood.

acquired immune deficiency syndrome (AIDS): a disease caused by the human immunodeficiency virus (HIV).

acrosome: a structure containing digestive enzymes, in the head of a sperm cell.

active immunity: long-term defence against a pathogen by antibody production in the body.

active site: the part of an enzyme molecule to which the substrate temporarily binds.

active transport: the movement of molecules or ions through a cell membrane from a region of lower concentration to a region of higher concentration (i.e. against a concentration gradient) using energy from respiration.

adaptation (adapted): the process, resulting from natural selection, by which populations become more suited to their environment over many generations.

adrenaline: a hormone secreted by the adrenal glands, which prepares the body for fight or flight.

aerobic respiration: chemical reactions that take place in mitochondria, which use oxygen to break down glucose and other nutrient molecules to release energy for the cell to use.

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alimentary canal: part of the digestive system; a long tube running from mouth to anus.

allele: alternative form of a gene.

alveoli: tiny air-filled sacs in the lungs where gas exchange takes place.

amino acids: substances with molecules containing carbon, hydrogen, oxygen and nitrogen; there are 20 different amino acids found in organisms.

amylase: an enzyme that catalyses the breakdown of starch to maltose.

anaerobic respiration: chemical reactions in cells that break down nutrient molecules to release energy, without using oxygen.

anther: the structure at the top of a stamen, inside which pollen grains are made.

antibiotic: a substance that is taken into the body, and which kills bacteria but does not affect human cells or viruses.

antibodies: molecules secreted by white blood cells, which bind to pathogens and help to destroy them.

antigen: a chemical that is recognised by the body as being 'foreign' (i.e., it is not part of the body's normal set of chemical substances) and stimulates the production of antibodies.

anus: the exit from the alimentary canal, through which faeces are removed.

aorta: the largest artery in the body, which receives oxygenated blood from the left ventricle and delivers it to the body organs

artery: a thick-walled vessel that takes high-pressure blood away from the heart.

artificial insemination (AI): introducing semen, containing sperm, to the reproductive organs of a female; fertilisation occurs in her body in the normal way.

artificial selection or selective breeding: choosing particular organisms with desired characteristics to breed together, and continuing this over many generations.

asexual reproduction: a process resulting in the production of genetically identical offspring from one parent.

assimilation: the uptake and use of nutrients by cells.

atria (singular: atrium): the thin-walled chambers at the top of the heart, which receive blood.

axon: a long, thin, fibre of cytoplasm that extends from the cell body of a neurone.

bacteria: unicellular organisms whose cells do not contain a nucleus.

balanced diet: a diet that contains all of the required nutrients, in suitable proportions, and the right amount of energy.

Benedict's solution: a blue liquid that turns orange-red when heated with a reducing sugar.

bile: an alkaline fluid produced by the liver, which helps with fat digestion.

bile duct: the tube that carries bile from the gall bladder to the duodenum.

biodiversity: the number of different species that live in an area.

biuret reagent: a blue solution that turns purple when mixed with amino acids or proteins.

breathing: using the muscles in the diaphragm, and the intercostal muscles, to change the volume of the thorax so that air is drawn into and pushed out of the lungs.

bronchiole: a small tube that takes air from a bronchus to every part of the lungs.

bronchus: one of the two tubes that takes air from the trachea into the lungs.

buffer solution: a liquid that has a known pH, and that keeps that pH steady all the time.

capillary: a tiny vessel with walls only one cell thick, that takes blood close to body cells.

captive breeding: keeping animals in captivity (e.g. in a zoo) and allowing them to breed, in order to increase the numbers in the population.

carbohydrases: enzymes that break down carbohydrates.

carbohydrates: substances that include sugars, starch and cellulose; they contain carbon, hydrogen and oxygen.

carnivore: an animal that gets its energy by eating other animals.

carpel: the female part of a flower.

carrier proteins (or protein carriers): protein molecules in cell membranes that can use energy to change shape and move ions or molecules into or out of a cell.

catalase: an enzyme that catalyses the breakdown of hydrogen peroxide to water and oxygen.

catalyst: a substance that increases the rate of a chemical reaction and is not changed by the reaction.

cell membrane: a very thin layer surrounding the cytoplasm of every cell; it controls what enters and leaves the cell.

cell sap: the fluid that fills the large vacuoles in plant cells.

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cell wall: a tough layer outside the cell membrane; found in the cells of plants, fungi and bacteria.

cells: the smallest units from which all organisms are made.

central nervous system (CNS): the brain and spinal cord.

cervix: a narrow opening leading from the uterus to the vagina.

chemical digestion: the breakdown of large molecules in food into smaller molecules, so that they can be absorbed.

chloroplasts: small structures found inside some plant cells, inside which photosynthesis takes place.

chromosome: a length of DNA, found in the nucleus of a cell; it contains genetic information in the form of many different genes.

circulatory system: a system of blood vessels with a pump and valves to ensure one-way flow of blood.

colon: the first part of the large intestine.

community: all of the populations of all the different species in an ecosystem.

complementary: with a perfect mirror-image shape.

concentration gradient: an imaginary 'slope' from a high concentration to a low concentration.

consumer: an organism that gets its energy by feeding on other organisms.

continuous variation: variation in which there is a continuous range of phenotypes between two extremes.

control: a standard sample that you use as a comparison, to find the effect of changing a variable.

coordination: ensuring that the actions of different parts of the body work together.

coronary arteries: vessels that deliver oxygenated blood to the heart muscle.

coronary heart disease (CHD): disease caused by blockage of the coronary arteries.

cuticle: a thin layer of wax that covers the upper surface of a leaf.

cytoplasm: the jelly-like material that fills a cell.

decomposer: an organism that gets its energy from dead or waste organic material.

dendrite: short fibre of cytoplasm in a neurone.

deoxygenated blood: blood containing only a little oxygen.

dependent variable: the variable that you measure, as you collect your results.

destarching: leaving a plant in the dark for long enough for it to use up its starch stores.

diaphragm: a muscle that separates the chest cavity from the abdominal cavity in mammals; it helps with breathing.

diet: the food eaten in one day.

diffusion: the net movement of particles from a region of their higher concentration to a region of their lower concentration (i.e. down a concentration gradient), as a result of their random movement.

digestion: the breakdown of food.

digestive system: the group of organs that carries out digestion of food.

diploid: having two complete sets of chromosomes.

discontinuous variation: variation in which there are distinct categories of phenotype, with no intermediates.

DNA: a molecule that contains genetic information, in the form of genes, that controls the proteins that are made in the cell.

dominant allele: an allele that is expressed if it is present (e.g. **G**).

dormant: inactive, with metabolic reactions taking place very slowly or not at all.

double circulatory system: a system in which blood passes through the heart twice on one complete circuit of the body.

drug: any substance taken into the body that modifies or affects chemical reactions in the body.

duodenum: the first part of the small intestine, into which the pancreatic duct and bile duct empty fluids.

ecology: the study of organisms in their environment.

ecosystem: a unit containing all of the organisms in a community and their environment, interacting together.

effectors: parts of the body that respond to a stimulus; muscles and glands are effectors.

egestion: the removal of undigested food from the body as faeces.

emulsifies: breaks down large drops of fat or oil into smaller droplets, increasing their surface area and allowing them to mix with watery liquids.

emulsion: a liquid containing two substances that do not fully mix; one of them forms tiny droplets dispersed throughout the other.

endangered: at serious risk of becoming extinct.

endocrine glands: glands that secrete hormones.

enzyme–substrate complex: the short-lived structure formed as the substrate binds temporarily to the active site of an enzyme.

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enzymes: proteins that are involved in all metabolic reactions, where they function as biological catalysts.

epidermis: the outer layer of tissue on a plant; also the outer layer of an animal's skin.

extinction: the complete loss of a species from Earth.

fats: lipids that are solid at room temperature.

fertile: able to reproduce.

fertilisation: the fusion of the nuclei of two gametes.

filament: the 'stalk' part of a stamen.

flaccid: a description of a plant cell that has lost its turgor pressure and is soft.

flagella (singular: flagellum): a long, whip-like 'tail' structure found on sperm cells, used for swimming.

follicle: a structure within an ovary, in which an egg develops.

food chain: a diagram showing the flow of energy from one organism to the next, beginning with a producer.

food web: a network of interconnected food chains.

foreign species: an organism that is not usually found in a habitat.

fully permeable: allows all molecules and ions to pass through it.

gall bladder: a small organ that stores bile, before the bile is released into the duodenum.

gamete: a sex cell; a cell with half the normal number of chromosomes, whose nucleus fuses with the nucleus of another gamete during sexual reproduction.

gas exchange: the diffusion of oxygen and carbon dioxide into and out of an organism's body.

gas exchange surface: a part of the body where gas exchange between the body and the environment takes place.

gene: a length of DNA that codes for one protein.

genetic diagram: a standard way of showing all the steps in making predictions about the probable genotypes and phenotypes of the offspring from two parents.

genotype: the genetic makeup of an organism in terms of the alleles present (e.g. **GG**).

glucagon: a hormone secreted by the pancreas, which increases blood glucose concentration.

glucose: a sugar that is used in respiration to release energy.

glycogen: a carbohydrate that is used as an energy store in animal cells.

goblet cells: cells found in the lining (epithelium) of the respiratory passages and digestive system, which secrete mucus.

guard cells: a pair of cells that surrounds a stoma and controls its opening; guard cells are the only cells in the epidermis that contain chloroplasts.

habitat: the place where an organism lives.

haemoglobin: a red pigment found in red blood cells, which can combine reversibly with oxygen; it is a protein.

haploid: having only a single set of chromosomes.

herbivore: an animal that gets its energy by eating plants.

heterozygous: having two different alleles of a particular gene (e.g. **Gg**).

high water potential: an area where there are a lot of water molecules, that is, a dilute solution.

homeostasis: the maintenance of a constant internal environment.

homozygous: having two identical alleles of a particular gene (e.g. **GG** or **gg**).

hormones: chemicals that are produced by a gland and carried in the blood, which alter the activities of their specific target organs.

host: an organism in which a pathogen lives and reproduces.

human immunodeficiency virus (HIV): a virus which destroys white blood cells and, therefore, reduces the ability of the immune system to defend against other pathogens.

humidity: how much water vapour is present in air.

hypothalamus: part of the brain that is involved in the control of body temperature.

ileum: the second part of the small intestine; most absorption takes place here.

immune response: the reaction of the body to the presence of an antigen; it involves the production of antibodies.

in vitro fertilisation (IVF): adding semen, containing sperm, to eggs in a container in a laboratory; fertilisation occurs in the container, and embryos can later be inserted into the body of a female.

independent variable: the variable that you change in an experiment.

infection: the entry of a pathogen into the body of a host.

infertile: not able to reproduce.

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ingestion: the taking of food and drink into the body.

inheritance: the transmission of genetic information from generation to generation.

insulin: a hormone secreted by the pancreas, which decreases blood glucose concentration.

intercostal muscles: muscles between the ribs, which raise and lower the rib cage when they contract and relax.

internal environment: the conditions inside the body.

iodine solution: a solution of iodine in potassium iodide; it is orange–brown, and turns blue–black when mixed with starch.

keratin: the protein that forms hair.

large intestine: a relatively wide part of the alimentary canal, consisting of the colon and rectum.

lipases: enzymes that break down lipids (fats and oils).

lipids: substances containing carbon, hydrogen and oxygen; they are insoluble in water and are used as energy stores in organisms.

liver: a large, dark red organ that carries out many different functions, including production of bile and the regulation of blood glucose concentration.

low water potential: an area where there are not many water molecules, that is, a concentrated solution.

lubricated: made smooth and slippery, to reduce friction.

lumen: the space in the centre of a tube, through which substances can move.

lymphocytes: white blood cells that secrete antibodies.

magnification: how many times larger an image is than an object.

maltase: an enzyme that catalyses the breakdown of maltose to glucose.

meiosis: reduction division in which the chromosome number is halved from diploid to haploid.

memory cells: long-lived cells produced by the division of lymphocytes that have contacted their antigen; memory cells are able to respond quickly to subsequent contact with the same antigen.

menstruation: the loss of the broken down uterus lining through the vagina.

metabolic reactions: chemical reactions that take place in living organisms.

metabolism: chemical reactions that take place in living organisms.

mitochondrion: a small structure in a cell, where aerobic respiration releases energy from glucose.

mitosis: nuclear division giving rise to genetically identical cells in which the chromosome number is maintained by the exact duplication of chromosomes.

monohybrid cross: a cross where we consider the inheritance of only one gene.

motor neurone: a neurone that transmits electrical impulses from the central nervous system to an effector.

MRSA: methicillin-resistant *Staphylococcus aureus*; bacteria that are resistant to the antibiotic methicillin.

mucus: a smooth, viscous fluid secreted by many different organs in the body.

mutation: a random change in a gene, which can produce new alleles; mutation involves a change in the base sequence in DNA.

native species: an organism that is typical of a particular habitat.

natural selection: a process in which individuals with advantageous features are more likely to survive, reproduce and pass on their alleles to the next generation.

nectar: a sweet liquid secreted by many insect- pollinated flowers, to attract their pollinators.

negative feedback: a mechanism that detects a move away from the set point, and brings about actions that take the value back towards the set point.

nerve: a group of neurone axons lying together (like an electrical cable containing many wires).

nerve impulse: an electrical signal that passes rapidly along an axon.

net movement: overall or average movement.

neurone: a cell that is specialised for conducting electrical impulses rapidly.

nucleus: a structure containing DNA in the form of chromosomes.

oesophagus: the tube leading from the mouth to the stomach.

oils: lipids that are liquid at room temperature.

optimum: best; for example, the optimum temperature of an enzyme is the temperature at which its activity is greatest.

organ: a structure made up of a group of tissues, working together to perform specific functions.

organ system: a group of organs with related functions, working together to perform body functions.

organism: a living thing.

osmosis: the diffusion of water molecules through a partially permeable membrane.

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osmosis (in terms of water potential): the net movement of water molecules from a region of higher water potential (dilute solution) to a region of lower water potential (concentrated solution) through a partially permeable membrane.

ovaries: organs that produce female gametes (eggs).

ovary: the part of the flower that holds the ovules.

overharvesting: the unsustainable removal of a crop or animal from its habitat.

oviducts: tubes leading from the ovaries to the uterus; also known as Fallopian tubes.

ovulation: the release of an egg from an ovary.

ovules: small structures that contain the female gametes.

oxygen debt: extra oxygen that is needed after anaerobic respiration has taken place, in order to break down the lactic acid produced.

oxygenated blood: blood containing a lot of oxygen.

palisade mesophyll: the layer of cells immediately beneath the upper epidermis, where most photosynthesis happens.

pancreas: a creamy-white organ lying close to the stomach, which secretes pancreatic juice; it also secretes the hormones insulin and glucagon, which are involved in the control of blood glucose concentration.

pancreatic duct: the tube that carries pancreatic fluid from the pancreas to the duodenum.

partially permeable: allows some molecules and ions to pass through, but not others.

particles: (in this context) the smallest pieces of which a substance is made; particles can be molecules, atoms or ions.

pathogens: microorganisms, such as bacteria, that cause disease.

penis: organ containing the urethra, through which urine and sperm are carried.

peripheral nervous system (PNS): the nerves outside the brain and spinal cord.

peristalsis: rhythmical muscular contractions that move food through the alimentary canal.

petals: coloured structures that attract insects or birds to a flower.

phagocytes: white blood cells that destroy pathogens by phagocytosis.

phagocytosis: taking bacteria or other small structures into a cell's cytoplasm, and digesting them with enzymes.

phenotype: the observable features of an organism.

phloem: a plant tissue made up of living cells joined end to end; it transports substances made by the plant, such as sucrose and amino acids.

photosynthesis: the process by which plants synthesise carbohydrates from raw materials using energy from light.

physical digestion: the breakdown of food into smaller pieces, without making any chemical changes to the molecules in the food.

plasma: the liquid part of blood.

plasmids: small, circular molecules of DNA, found in many prokaryotic cells in addition to the main, much larger circle of DNA.

plasmolysed: a description of a cell in which the cell membrane tears away from the cell wall.

platelets: tiny cell fragments present in blood, which help with clotting.

pollen grains: small structures which contain the male gametes of a flower.

pollination: the transfer of pollen grains from the male part of the plant (anther of stamen) to the female part of the plant (stigma).

population: a group of organisms of one species, living in the same area at the same time.

primary consumer: an animal that gets its energy by eating plants; it is the first consumer in a food chain.

producer: an organism that makes its own organic nutrients, generally using energy from sunlight, through photosynthesis.

product: the new substance formed by a chemical reaction.

prokaryotic cells: cells with no nucleus; bacteria have prokaryotic cells.

prostate gland: organ that produces a nutritious fluid in which sperm are transported.

protease: an enzyme that catalyses the breakdown of protein to amino acids.

protein: a substance whose molecules are made of many amino acids linked together; each different protein has a different sequence of amino acids.

puberty: the time at which sexual maturity is reached.

pulmonary artery: the artery that carries deoxygenated blood from the right ventricle to the lungs.

pulmonary veins: the veins that carry oxygenated blood from the lungs to the left atrium of the heart.

pulse rate: the number of times an artery expands and recoils in one minute; it is a measure of heart rate.

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Punnett square: the part of a genetic diagram that shows the predicted genotypes and phenotypes that can result from the random fusion of the male and female gametes.

range: the lowest to the highest value.

receptors: cells or groups of cells that detect stimuli.

recessive allele: an allele that is only expressed when there is no dominant allele of the gene present (e.g. **g**).

rectum: the second part of the large intestine, where faeces are produced and stored.

red blood cells: biconcave blood cells with no nucleus, which transport oxygen.

reducing sugar: a sugar, such as glucose, which turns Benedict's solution orange-red when they are heated together.

reduction division: a term used to describe what happens in meiosis, where the number of chromosomes is halved (reduced).

reflex action: a means of automatically and rapidly integrating and coordinating stimuli with the responses of effectors.

reflex arc: a series of neurones (sensory, relay and motor) that transmit electrical impulses from a receptor to an effector.

relay neurone: a neurone that transmits electrical impulses within the central nervous system.

respiration: the chemical reactions in cells that break down nutrient molecules and release energy for metabolism.

ribosome: very small structure in a cell that uses information on DNA to make protein molecules.

salivary glands: groups of cells close to the mouth, which secrete saliva into the salivary ducts.

scrotum: the sac that contains the testes.

secondary consumer: an animal that eats a primary consumer.

secrete: make a useful substance and then send it out of the cell where it is made, to be used in another part of the body.

seed: the structure that develops from an ovule after fertilisation; it contains an embryo plant.

seed bank: facility in which seeds of different plant species, or crop varieties, are stored for long periods of time, in order to conserve as many different species and varieties as possible.

selection pressure: something in the environment that affects the chance that individuals with different features will survive and reproduce.

sense organ: a group of receptor cells that are able to respond to a specific stimulus.

sensitivity: the ability to detect and respond to changes in the internal or external environment.

sensory neurone: a neurone that transmits electrical impulses from a receptor to the central nervous system.

sepals: leaf-like structures that form a ring outside the petals of a flower.

septum: the structure that separates the left and right sides of the heart.

set point: the normal value or range of values for a particular parameter – for example, the normal range of blood glucose concentration or the normal body temperature.

sexual reproduction: a process involving the fusion of the nuclei of two gametes to form a zygote and the production of offspring that are genetically different from each other.

sexually transmitted infection (STI): a disease caused by pathogens that are transmitted during sexual contact.

sink: part of a plant to which sucrose or amino acids are being transported, and where they are used or stored.

small intestine: a long, narrow part of the alimentary canal, consisting of the duodenum and ileum.

source: part of a plant that releases sucrose or amino acids, to be transported to other parts.

species: a group of organisms that can reproduce to produce fertile offspring.

specificity: of enzymes, only able to act on a particular (specific) substrate.

sperm duct: a tube that transports sperm from the testis to the urethra.

sphincter muscles: rings of muscle that can contract to close a tube.

spongy mesophyll: the layer of cells immediately beneath the palisade mesophyll, where some photosynthesis happens; this tissue contains a lot of air spaces between the cells.

stamens: the male parts of a flower.

starch: a carbohydrate that is used as an energy store in plant cells.

starch grains: structures that consist of thousands of starch molecules, stored in some plant cells.

stigma: the part of a flower that receives pollen.

stimuli (singular: stimulus): changes in the environment that can be detected by organisms.

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stomach: a wide part of the alimentary canal, in which food can be stored for a while, and where the digestion of protein begins.

stomata (singular: stoma) openings in the surface of a leaf, most commonly in the lower surface; they are surrounded by pairs of guard cells, which control whether the stomata are open or closed.

style: the part of a carpel that connects the stigma to the ovary.

substrate: the substance that an enzyme causes to react.

sucrase: an enzyme that breaks down sucrose.

sucrose: a sugar whose molecules are made of glucose and another similar molecule (fructose) linked together.

sugars: carbohydrates that have relatively small molecules; they are soluble in water and they taste sweet.

sweat gland: a structure found in the skin of mammals, which secretes a watery fluid onto the skin surface to reduce body temperature.

symptoms: features that you experience when you have a disease.

target organs: organs whose activity is altered by a hormone.

tertiary consumer: an animal that eats a secondary consumer.

testes (singular: testis): organs in which the male gametes (sperm) are made.

thorax: the chest; the part of the body from the neck down to the diaphragm.

tissue: a group of similar cells that work together to perform a particular function.

toxin: a poisonous substance; a chemical that damages cells.

trachea: the tube through which air travels to the lungs; it has rings of cartilage in its walls, to support it.

translocation: the movement of sucrose and amino acids in phloem from sources to sinks.

transmissible disease: a disease that can be passed from one host to another; transmissible diseases are caused by pathogens.

transmission: the movement of a pathogen from one host to another.

transpiration: the loss of water vapour from leaves.

trophic level: the position of an organism in a food chain, food web or pyramid of biomass or numbers.

turgid: a description of a plant cell that is tight and firm.

turgor pressure: the pressure of the water pushing outwards on a plant cell wall.

uterus: the organ in which a fetus develops before birth; also known as the womb.

vaccine: a harmless preparation of dead or inactivated pathogens that is injected into the body to induce an immune response.

vacuole: a fluid-filled space inside a cell, separated from the cytoplasm by a membrane.

vagina: opening from the uterus to the outside of the body.

valves: structures that allow a liquid to flow in one direction only.

variation: differences between the individuals of the same species.

vascular bundles: collections of xylem tubes and phloem vessels running side by side, which form the veins in a leaf.

vasoconstriction: narrowing of arterioles, caused by the contraction of the muscle in their walls.

vasodilation: widening of arterioles, caused by the relaxation of the muscle in their walls.

vein: a thin-walled vessel that takes low-pressure blood back to the heart.

venae cavae (singular: vena cava): the large veins that bring deoxygenated blood to the right atrium.

ventilation: the movement of air into and out of the lungs, by breathing movements.

ventricles: the thick-walled chambers at the base of the heart, which pump out blood.

vesicle: a very small vacuole.

water potential gradient: a difference in water potential between two areas.

white blood cells: blood cells with a nucleus, which help to defend against pathogens.

wilting (of a plant): losing more water than it can take up, so the cells lose their turgidity.

xylem: a plant tissue made up of dead, empty cells joined end to end; it transports water and mineral ions and helps to support the plant.

zygote: a cell that is formed by the fusion of two gametes.

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Chemistry

accuracy: how close a value is to the true value.

acid: a solution of an acid turns litmus red and has a pH below 7.

acid–base reaction: a chemical reaction between an acid and a base.

acid–base titration: a method of quantitative chemical analysis where an acid is added slowly to a base until it has been neutralised, or vice versa.

acid rain: rain that has been made more acidic than normal by the presence of dissolved pollutants such as sulfur dioxide (SO_2) and oxides of nitrogen (nitrogen oxides, NO_x).

acidic oxide: oxide of a non-metal that will react with bases and dissolve in water to produce an acid solution.

activation energy (*Ea*): the minimum energy required to start a chemical reaction; for a reaction to take place the colliding particles must possess at least this amount of energy.

addition polymer: a polymer formed by an addition reaction – the monomer molecules contain a carbon–carbon double bond.

addition reaction: a reaction in which a simple molecule adds across the carbon–carbon double bond of an alkene.

adsorption: the attachment of molecules to a solid surface.

alkali: a soluble base; a solution of an alkali turns litmus blue and has a pH above 7.

alkali metals: elements in Group I of the Periodic Table; form an alkaline solution when reacted with water; generally the most reactive group of metals.

alkanes: a series of hydrocarbons with the general formula C_nH_{2n+2}; they are saturated compounds as they have only single bonds between atoms in their structure.

alkenes: a series of hydrocarbons with the general formula C_nH_{2n}; they are unsaturated compounds as they contain carbon–carbon double bonds.

alloys: mixtures of elements (usually metals) designed to have the properties useful for a particular purpose, e.g. solder (an alloy of tin and lead) has a low melting point.

amide link (or peptide link): the link between monomers in a protein or nylon, formed by a condensation reaction between a carboxylic acid group on one monomer and an amine group on the next monomer.

amino acids: naturally occurring organic compounds that possess both an amino ($–NH_2$) group and an acid (–COOH) group in the molecule; there are 20 naturally occurring amino acids and they are polymerised in cells to make proteins.

amphoteric compound: a compound (hydroxide or metal oxide) that can react with either an acid or an alkali to give a salt and water.

anhydrous: an adjective to describe a substance without water combined with it.

anion: a negative ion that would be attracted to the anode in electrolysis.

anode: the electrode in any type of cell at which oxidation (the loss of electrons) takes place; in electrolysis it is the positive electrode.

anomalous: something that is unusual or unexpected and deviates from the normal; one of a series of repeated experimental results that is much larger or smaller than the others is an anomalous result.

anti-bumping granules: small granules that help reduce the size of bubbles formed when a liquid boils; used for safety to stop the flask shaking.

atmosphere: the layer of air and water vapour surrounding the Earth.

atom: the smallest particle of an element that can take part in a chemical reaction.

atomic theory: a model of the atom in which electrons can only occupy certain shells (or energy levels) moving outwards from the nucleus of an atom.

Avogadro constant: the number (6.02×10^{23}) of characteristic particles in 1 mole of a substance.

Avogadro's law: equal volumes of any gas, under the same conditions of temperature and pressure, contain the same number of particles.

balanced chemical equation: a summary of a chemical reaction using chemical formulae; the total number of any of the atoms involved is the same on both the reactant and product sides of the equation.

base: a substance that neutralises an acid, producing a salt and water as the only products.

basic oxide: oxide of a metal that will react with acids to neutralise the acid.

binary substance: a substance composed from two different elements.

blast furnace: a furnace for extracting metals (particularly iron) by reduction with carbon that uses hot air blasted in at the base of the furnace to raise the temperature.

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boiling: the process of change from liquid to gas at the boiling point of the substance; a condition under which gas bubbles are able to form within a liquid – gas molecules escape from the body of a liquid, not just from its surface.

boiling point: the temperature at which a liquid boils, when the pressure of the gas created above the liquid equals atmospheric pressure.

bond energy: the energy required to break a particular type of covalent bond.

brass: an alloy of copper and zinc; this alloy is hard.

burette: a piece of glass apparatus used for delivering a variable volume of liquid accurately.

calibration: the process of checking that the device gives accurate values by using it to read samples with known values.

catalyst: a substance that increases the rate of a chemical reaction but itself remains unchanged at the end of the reaction.

catalytic converter: a device for converting polluting exhaust gases from cars into less dangerous emissions.

catalytic cracking: the decomposition of long-chain alkanes into alkenes and alkanes of lower relative molecular mass; involves passing the larger alkane molecules over a catalyst heated to 500 °C.

cathode: the electrode in any type of cell at which reduction (the gain of electrons) takes place; in electrolysis it is the negative electrode.

cation: a positive ion that would be attracted to the cathode in electrolysis.

chemical bonding: the strong forces that hold atoms (or ions) together in the various structures that chemical substances can form; this includes metallic bonding, covalent bonding and ionic bonding.

chemical change (reaction): a change in which a new substance is formed.

chemical feedstock: a chemical element or compound which can be used as a raw material for an industrial process making useful chemical products.

chemical formula: a shorthand method of representing chemical elements and compounds using the symbols of the elements.

chemical symbol: a letter or group of letters representing an element in a chemical formula.

chromatogram: the result of a paper chromatography run, showing where the spots of the samples have moved to.

chromatography: a technique employed for the separation of mixtures of dissolved substances, which was originally used to separate coloured dyes.

clean dry air: containing no water vapour and only the gases that are always present in the air.

climate change: changes in weather patterns brought about by global warming.

coal: a black, solid fossil fuel formed underground over geological periods of time by conditions of high pressure and temperature acting on decayed vegetation.

collision theory: a theory that states that a chemical reaction takes place when particles of the reactants collide with sufficient energy to initiate the reaction.

combustion: a chemical reaction in which a substance reacts with oxygen; the reaction is exothermic.

complete combustion: a type of combustion reaction in which a fuel is burnt in a plentiful supply of oxygen; the complete combustion of hydrocarbon fuels produces only carbon dioxide and water.

compound: a substance formed by the chemical combination of two or more elements in fixed proportions.

compound ion: an ion made up of several different atoms covalently bonded together and with an overall charge (can also be called a molecular ion; negatively charged compound ions containing oxygen can be called oxyanions).

condensation: the change of a vapour or a gas into a liquid; during this process heat is given out to the surroundings.

condensation polymer: a polymer formed by a condensation reaction, e.g. nylon is produced by the condensation reaction between 1,6-diaminohexane and hexanedioic acid; this is the type of polymerisation used in biological systems to produce proteins, nucleic acids and polysaccharides.

condensation reaction: a reaction where two or more substances combine together to make a larger compound, and a small molecule is eliminated (given off).

controlled variable: a variable that is kept the same during an investigation.

corrosive: a corrosive substance (e.g. an acid) is one that can dissolve or 'eat away' at other materials (e.g. wood, metals or human skin).

covalent bonding: chemical bonding formed by the sharing of one or more pairs of electrons between atoms.

crystallisation: the process of forming crystals from a saturated solution.

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decomposition: a type of chemical reaction where a compound breaks down into simpler substances.

dependent variable: the variable that is measured during a scientific investigation.

desalination: the removal of dissolved salts and minerals from seawater to produce drinking water.

desulfurisation: the removal of sulfur dioxide from the fumes of power stations.

diatomic molecules: molecules containing two atoms, e.g. hydrogen, H_2.

diffusion: the process by which different fluids mix as a result of the random motions of their particles.

displacement reaction: a reaction in which a more reactive element displaces a less reactive element from a solution of its salt.

displayed formula: a representation of the structure of a compound that shows all the atoms and bonds in the molecule.

distillate: the liquid collected in the receiving flask during distillation.

dot-and-cross diagram: a diagram drawn to represent the bonding in a molecule, or the electrons in an ion; usually, only the outer electrons are shown and they are represented by dots or crosses depending on which atom they are from.

ductile: a word used to describe the property that metals can be drawn out and stretched into wires.

electrical conductivity: the ability to conduct electricity.

electrical conductor: a substance that conducts electricity but is not chemically changed in the process.

electrical insulator: a substance that does not conduct electricity.

electrodes: the points where the electric current enters or leaves a battery or electrolytic cell.

electrolysis: the breakdown of an ionic compound, molten or in aqueous solution, by the use of electricity.

electrolyte: an ionic compound that will conduct electricity when it is molten or dissolved in water; electrolytes will not conduct electricity when solid.

electrolytic cell: a cell consisting of an electrolyte and two electrodes (anode and cathode) connected to an external DC power source where positive and negative ions in the electrolyte are separated and discharged.

electron: a subatomic particle with negligible mass and a relative charge of −1; electrons are present in all atoms, located in the shells (energy levels) outside the nucleus.

electron shells (energy levels): (of electrons) the allowed energies of electrons in atoms; electrons fill these shells (or levels) starting with the one closest to the nucleus.

electronic configuration: a shorthand method of describing the arrangement of electrons within the electron shells (or energy levels) of an atom; also referred to as electronic structure. This is given as number of electrons in the first shell, number of electrons in second shell, number of electrons in third shell, and so on.

electroplating: a process of electrolysis in which a metal object is coated (plated) with a layer of another metal.

electrostatic forces: strong forces of attraction between particles with opposite charges; such forces are involved in ionic bonding.

element: a substance that cannot be further divided into simpler substances by chemical methods; all the atoms of an element contain the same number of protons.

end-point: the point in a titration when the indicator just changes colour, showing that the reaction is complete.

endothermic changes: a process or chemical reaction that takes in heat from the surroundings; ΔH for an endothermic change has a positive value.

energy level diagram (reaction pathway diagram): a diagram that shows the energy levels of the reactants and products in a chemical reaction and shows whether the reaction is exothermic or endothermic.

enthalpy (H): the thermal (heat) content of a system.

enthalpy change (ΔH): the heat change during the course of a reaction (also known as heat of reaction); can be either exothermic (a negative value) or endothermic (a positive value).

evaporation: a process occurring at the surface of a liquid, involving the change of state from a liquid into a vapour at a temperature below the boiling point.

exothermic changes: a process or chemical reaction in which heat energy is produced and released to the surroundings; ΔH for an exothermic change has a negative value.

filtrate: the liquid that passes through the filter paper during filtration.

filtration: the separation of a solid from a liquid, using a fine filter paper which does not allow the solid to pass through.

fluid: a gas or a liquid; fluids are able to flow.

formula unit: this unit of an element or compound is the molecule or group of ions defined by the chemical formula of the substance.

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fossil fuels: fuels, such as coal, oil and natural gas, formed underground over geological periods of time from the remains of plants and animals.

fractional distillation: a method of distillation using a fractionating column, used to separate liquids with different boiling points.

fractionating column: the vertical column that is used to bring about the separation of liquids in fractional distillation.

fractions (from distillation): the different mixtures that distil over at different temperatures during fractional distillation.

fuel: a substance that can be used as a source of energy, usually by burning (combustion).

fuel cell: a device for continuously converting chemical energy into electrical energy using a combustion reaction; a hydrogen–oxygen fuel cell uses the reaction between hydrogen and oxygen.

functional group: the atom or group of atoms responsible for the characteristic reactions of a compound.

galvanising: the protection of iron and steel objects by coating with a layer of zinc.

general formula: an algebraic formula that describes all members of a homologous series, e.g. for alkanes C_nH_{2n+2}.

global warming: a long-term increase in the average temperature of the Earth's surface, which may be caused in part by human activities.

greenhouse effect: the natural phenomenon in which thermal energy (heat) from the Sun is 'trapped' at the Earth's surface by certain gases in the atmosphere (greenhouse gases).

greenhouse gas: a gas that absorbs heat reflected from the surface of the Earth, stopping it escaping the atmosphere.

group: vertical column of the Periodic Table containing elements with similar chemical properties; atoms of elements in the same group have the same number of electrons in their outer energy levels.

group number: the number of the vertical column that an element is in on the Periodic Table.

half-equations: ionic equations showing the separate oxidation and reduction steps in redox reactions, including the reactions at the anode (oxidation) and cathode (reduction) in an electrolytic cell.

halides: compounds formed between an element and a halogen, e.g. sodium iodide.

halogen: element in Group VII of the Periodic Table; generally the most reactive group of non-metals.

halogen displacement reactions: reactions in which a more reactive halogen displaces a less reactive halogen from a solution of its salt.

hematite: the major ore of iron, iron(III) oxide.

homologous series: a family of similar compounds with similar chemical properties due to the presence of the same functional group.

hydrated substance: a substance that is chemically combined with water; *hydrated salts* are an important group of such substances.

hydration: the addition of the elements of water across a carbon–carbon double bond; H– adds to one carbon, and –OH to the other.

hydrocarbon: organic compound that contains carbon and hydrogen only; the alkanes and alkenes are two series of hydrocarbons.

hydrogenation: an addition reaction in which hydrogen is added across the double bond in an alkene.

incomplete combustion: a type of combustion reaction in which a fuel is burnt in a limited supply of oxygen; the incomplete combustion of hydrocarbon fuels produces carbon, carbon monoxide and water.

independent variable: the variable that is altered during a scientific investigation.

indicator: a substance that changes colour when added to acidic or alkaline solutions, e.g. litmus or phenolphthalein.

inert: a term that describes substances that do not produce a chemical reaction when another substance is added.

inert electrode: an electrode that is made from a material that will not interact with the electrolyte or the products of electrolysis.

insoluble: a substance that does not dissolve in a particular solvent.

intermolecular forces: the weak attractive forces that act between molecules.

intermolecular space: the space between atoms or molecules in a liquid or gas. The intermolecular space is small in a liquid, but relatively very large in a gas.

ionic bonding: a strong electrostatic force of attraction between oppositely charged ions.

ionic equation: the simplified equation for a reaction involving ionic substances: only those ions which change during the reaction are shown.

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ions: charged particles made from an atom, or groups of atoms (compound ions), by the loss or gain of electrons.

isotopes: atoms of the same element that have the same proton number but a different nucleon number.

kinetic particle theory: a theory which accounts for the bulk properties of the different states of matter in terms of the movement of particles (atoms or molecules); the theory explains what happens during changes in physical state.

lattice: a regular three-dimensional arrangement of atoms, molecules or ions in a crystalline solid.

limestone: a form of calcium carbonate ($CaCO_3$).

limiting reactant: the reactant that is not in excess.

litmus: the most common indicator; turns red in acid and blue in alkali.

malleability: the ability of a substance to be bent or beaten into shape. Malleable is the word used to describe a substance that can be bent or beaten into shape.

malleable: a word used to describe the property that allows metals to be bent and beaten into sheets.

mass number (or nucleon number) (*A*): the total number of protons and neutrons in the nucleus of an atom.

matter: anything that occupies space and has mass.

melting point (m.p.): the temperature at which a solid turns into a liquid – it has the same value as the freezing point; a pure substance has a sharp melting point.

metallic bonding: an electrostatic force of attraction between the mobile 'sea' of electrons and the regular array of positive metal ions within a solid metal.

metalloid (semi-metal): element that shows some of the properties of metals and some of non-metals, e.g. boron and silicon.

methyl orange: an indicator which is red in acid and yellow in alkali.

mineral: a naturally occurring rock containing a particular compound.

mixture: two or more elements or molecules mixed together without being chemically bonded.

molar gas volume: the volume of 1 mole of any gas under specific conditions of temperature and pressure (24 dm^3 at r.t.p.).

molar mass: the mass, in grams, of 1 mole of a substance.

mole: the measure of amount of substance in chemistry; 1 mole of a substance has a mass equal to its relative formula mass in grams – that amount of substance contains 6.02×10^{23} (the Avogadro constant) atoms, molecules or formula units depending on the substance considered.

molecular formula: a formula that shows the actual number of atoms of each element present in a molecule of the compound.

molecule: a group of atoms held together by covalent bonds.

monomer: a small molecule, such as ethene, which can be polymerised to make a polymer.

natural gas: a fossil fuel formed underground over geological periods of time by conditions of high pressure and temperature acting on the remains of dead sea creatures; natural gas is more than 90% methane.

neutralisation: a chemical reaction between an acid and a base to produce a salt and water only.

neutron: an uncharged subatomic particle present in the nucleus of atoms; a neutron has a mass of 1 relative to a proton.

noble gases: elements in Group VIII; a group of stable, very unreactive gases.

non-electrolyte: liquid or solution that does not take part in electrolysis; it does not contain ions.

non-renewable (finite) resources: sources of energy, such as fossil fuels, and other resources formed in the Earth over many millions of years, which we are now using up at a rapid rate and cannot replace.

nucleus: (of an atom) the central region of an atom that is made up of the protons and neutrons of the atom; the electrons orbit around the nucleus in different 'shells' or 'energy levels'.

ore: a naturally occurring mineral from which a metal can be extracted.

organic chemistry: studies on the structure, properties and reactions of organic compounds that contain carbon in covalent bonding.

oxidation number: a number given to show whether an element has been oxidised or reduced; the oxidation number of a simple ion is simply the charge on the ion.

paper chromatography: a simple type of chromatography used to separate the components of soluble substances based on their rate of migration in a solvent (mobile phase) on sheets of filter paper (stationary phase).

particulates: very tiny solid particles produced during the combustion of fuels.

period: a horizontal row of the Periodic Table.

period number: the horizontal row of the Periodic Table that an element is in.

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Periodic Table: a table of elements arranged in order of increasing proton number (atomic number) to show the similarities of the chemical elements with related electronic configurations.

petroleum: a fossil fuel formed underground over many millions of years by conditions of high pressure and temperature acting on the remains of dead sea creatures.

pH scale: a scale running from 0 to 14, used for expressing the acidity or alkalinity of a solution; a neutral solution has a pH of 7.

photochemical smog: a form of local atmospheric pollution found in large cities in which several gases react with each other to produce harmful products.

photosynthesis: the chemical process by which plants synthesise glucose from atmospheric carbon dioxide and water, giving off oxygen as a by-product; the energy required for the process is captured from sunlight by chlorophyll molecules in the green leaves of the plants.

physical change: a change in the physical state of a substance or the physical nature of a situation that does not involve a change in the chemical substance(s) present.

pollutants: substances, often harmful, which are added to another substance.

polyamide: a polymer where the monomer units are joined together by amide (peptide) links, e.g. nylon and proteins.

polymer: a substance consisting of very large molecules made by polymerising a large number of repeating units, or monomers.

polymerisation: the chemical reaction in which molecules (monomers) join together to form a long-chain polymer.

porous pot: an unglazed pot that has channels (pores) through which gases can pass.

precipitate: an insoluble salt formed during a precipitation reaction.

precipitation: the sudden formation of a solid when either two solutions are mixed or a gas is bubbled into a solution.

precipitation reaction: a reaction in which an insoluble salt is prepared from two aqueous solutions.

precision: the degree to which repeat measurements are consistent (close to each other).

products (in a chemical reaction): the substance(s) produced by a chemical reaction.

proteins: polymers of amino acids formed by a condensation reaction; they have a wide variety of biological functions.

proton: a subatomic particle with a relative atomic mass of 1 and a charge of +1 found in the nucleus of all atoms.

proton number (or atomic number) (Z): the number of protons in the nucleus of an atom.

pure substance: a single chemical element or compound; it melts and boils at definite precise temperatures.

qualitative: the process used to determine the presence or absence of a substance in a given sample.

quantitative: the ability to put numerical values to the properties being studied.

quantitative analysis: the process used to determine the amount or percentage of a substance in a given sample.

random errors: these are unpredictable variations in results caused by factors such as human errors.

reactants (in a chemical reaction): the chemical substances that react together in a chemical reaction.

reaction rate: a measure of how fast a reaction takes place.

reactivity: the ease with which a chemical substance takes part in a chemical reaction.

reactivity series (of metals): an order of reactivity, giving the most reactive metal first, based on results from a range of experiments involving metals reacting with oxygen, water, dilute hydrochloric acid and metal salt solutions.

redox reaction: a reaction involving both reduction and oxidation.

relative formula mass (M_r): the sum of all the relative atomic masses of the atoms present in a 'formula unit' of a substance.

relative molecular mass (M_r): the sum of all the relative atomic masses of the atoms present in a molecule.

renewable (resources): sources of energy and other resources that cannot run out provided they are managed sustainably, or that can be made at a rate faster than our current rate of use.

repeatability: where an experiment (or series of experiments) can be repeated using the same method and obtain *reproducible* (similar) results.

reproducible: data when several different people have performed an experiment with similar variables and obtained similar results.

residue: the solid left behind in the filter paper after filtration has taken place.

resolution: the smallest division on the instrument, e.g. this could be 1 mm on a ruler or 0.1 g on a balance.

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respiration: the chemical reaction (a combustion reaction) by which biological cells release the energy stored in glucose for use by the cell or the body; the reaction is exothermic and produces carbon dioxide and water as the chemical by-products.

R_f value: in chromatography, the ratio of the distance travelled by the solute to the distance travelled by the solvent front.

room temperature and pressure (r.t.p.): the standard values are 25 °C/298 K and 101.3 kPa/1 atmosphere pressure.

rusting: the corrosion of iron and steel to form rust (hydrated iron(III) oxide).

sacrificial protection: a method of rust protection involving the attachment of blocks of a metal more reactive than iron to a structure; this metal is corroded rather than the iron or steel structure.

salt: ionic compound made by the neutralisation of an acid with a base (or alkali), e.g. copper(II) sulfate and potassium nitrate.

saturated hydrocarbon: hydrocarbon molecule in which all the carbon–carbon bonds are single covalent bonds.

'sea' of delocalised electrons: term used for the free, mobile electrons between the positive ions in a metallic lattice.

simple distillation: a distillation method for separating the liquid solvent from a solution containing dissolved solids.

slag: a molten mixture of impurities, mainly calcium silicate, formed in the blast furnace.

soluble: a solute that dissolves in a particular solvent.

solvent front: the moving boundary of the liquid solvent that moves up the paper during chromatography.

stainless steel: an alloy of iron that resists corrosion; this steel contains a significant proportion of chromium which results in the alloy being resistant to rusting.

state symbols: symbols used to show the physical state of the reactants and products in a chemical reaction.

states of matter: solid, liquid and gas are the three states of matter in which any substance can exist, depending on the conditions of temperature and pressure.

structural formula: the structural formula of an organic molecule shows how all the groups of atoms are arranged in the structure; ethanol, CH_3CH_2OH, for example.

structural isomerism: a property of compounds that have the same molecular formula but different structural formulae; the individual compounds are known as *structural isomers*.

subatomic particles: very small particles – protons, neutrons and electrons – from which all atoms are made.

systematic errors: these are consistent errors that may arise because of a problem with the experimental design or in a piece of equipment being used.

thermal conductivity: the ability to conduct heat.

titration: a method of quantitative analysis using solutions: one solution is slowly added to a known volume of another solution using a burette until an end-point is reached.

titre: the volume of solution added from the burette during a titration.

transition metals (transition elements): elements from the central region of the Periodic Table; they are hard, strong, dense metals that form compounds that are often coloured.

universal indicator: a mixture of indicators that has different colours in solutions of different pH.

unsaturated hydrocarbon: hydrocarbon whose molecule contains at least one carbon–carbon double or triple bond.

volatile: term that describes a liquid that evaporates easily; it is a liquid with a low boiling point because there are only weak intermolecular forces between the molecules in the liquid.

volatility: the property of how easily a liquid evaporates.

volumetric pipette: a pipette used to measure out a volume of solution accurately.

word equation: a summary of a chemical reaction using the chemical names of the reactants and products.

zero error: a type of systematic error in a measuring instrument, e.g. the reading on a balance may not reset to zero when there is nothing on the balance.

Physics

a.c. generator: a device such as a dynamo used to generate alternating current.

acceleration: the rate of change of an object's velocity.

acceleration of free fall (or the acceleration due to gravity): the acceleration of any object falling freely under gravity.

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activity: the rate at which nuclei decay in a sample of a radioactive substance.

air resistance: friction acting on an object moving through air.

alpha decay: the decay of a radioactive nucleus by the emission of an α-particle.

alpha particle (α-particle): a particle made up of two protons and two neutrons; it is emitted by an atomic nucleus during radioactive decay.

alternating current (a.c.): electric current that (periodically) changes direction.

ammeter: a meter for measuring electric current.

ampere, amp (A): the SI unit of electric current.

amplitude: the greatest height or depth of a wave from its undisturbed position.

analogue: display has hands (or a needle) and is often not very precise.

angle of incidence: the angle between the incident ray and the normal drawn at the point where the ray hits the surface.

angle of reflection: the angle between the reflected ray and the normal drawn at the point where the ray hits the surface.

angle of refraction: the angle between a refracted ray and the normal to the surface at the point where it passes from one medium to another.

anticlockwise: turning in the opposite direction to the hands on a clock.

asteroid: lump of rock which orbits the Sun.

atom: the smallest part of an element that can exist.

attractive forces: forces between particles which hold the particles in fixed positions in a solid and close together in a liquid.

average speed: the speed calculated from total distance travelled divided by total time taken.

background radiation: the radiation from the environment to which we are exposed all the time.

bar magnet: a rectangular-shaped permanent magnet with a north pole at one end and a south pole at the other.

battery: two or more electrical cells connected together in series.

beta decay: the decay of a radioactive nucleus by the emission of a β-particle.

beta particle (β-particle): a high-speed electron that is emitted by an atomic nucleus during radioactive decay.

biofuel: material, recently living, used as a fuel.

black hole: the final stage in the life cycle of a star that started with more than eight solar masses; it has enough mass left over after exploding as a supernova to collapse to a point where gravity is so strong that not even light can escape.

boiler: device where thermal energy is transferred to water to turn it into steam.

boiling: changing from liquid to gas at a fixed temperature called the boiling point.

boiling point: the temperature at which a liquid changes to a gas (at constant pressure).

Brownian motion: the motion of small particles suspended in a liquid or gas, caused by molecular bombardment.

cell: a device that provides an electromotive force (e.m.f.) in a circuit by means of a chemical reaction.

centre of gravity: all the mass of an object could be located here and the object would behave the same (when ignoring any spin).

changes of state: changing from one state of matter to another.

charge: carried around a circuit by the current; negative charge is carried by electrons.

chemical energy: energy stored in bonds between atoms that can be released when chemical reactions take place.

clockwise: turning in the same direction as the hands on a clock.

commutator: a device used to allow current to flow to and from the coil of a d.c. motor or generator.

compression: a region of a longitudinal wave where the particles are pushed together.

condensing: changing from gas to liquid.

convection: the transfer of thermal energy through a material by the movement of the material itself.

convection current: the transfer of thermal energy by the motion of a fluid.

conventional current: the direction positive charges would flow in a complete circuit, from the positive to negative terminals of a cell, and opposite to the direction that electrons flow.

converging lens: a lens that causes rays of light parallel to the axis to converge at the principal focus.

count rate: the number of decaying radioactive atoms detected each second (or minute, or hour).

crest/peak: the highest point of a wave.

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critical angle: the minimum angle of incidence at which total internal reflection occurs.

current: the rate at which electric charge passes a point in a circuit.

delocalised (mobile) electrons: electrons which are not attached to an atom.

density: the ratio of mass to volume for a substance.

diffraction: the spreading out of a wave as it travels through a gap.

digital: display shows numbers and is often precise.

diminished: used to describe an image which is smaller than the object.

direct current (d.c.): electric current that flows in the same direction all the time.

dispersion: the separation of different wavelengths of light because they are refracted through different angles.

displacement: moving something to another place; for example, water is moved out of the way (upwards) when an object is lowered into it.

doing work: transferring energy by means of a force.

double insulated: when the electric circuit for an electrical appliance is placed inside a case made from an electrical insulator so that it is impossible for a live wire to touch the outer casing.

earthed: when the case of an electrical appliance is connected to the earth wire of a three-pin plug; the earth wire is electrically connected to the ground to prevent current passing through anyone touching a faulty appliance.

efficiency: the fraction (or percentage) of energy supplied that is usefully transferred.

elastic (strain) energy: energy stored in the changed shape of an object.

electric field: a region of space in which an electric charge will experience a force.

electrical conductor: a substance that allows the flow of electrons (electric current).

electrical insulator: a substance that inhibits the flow of electrons (electric current).

electrical power: the rate at which electrical energy is transferred.

electromagnet: a coil of wire that acts as a magnet when an electric current passes through it.

electromagnetic induction: the production of an e.m.f. across an electrical conductor when there is relative movement between the conductor and a magnetic field.

electromagnetic spectrum: a range of electromagnetic waves with different wavelengths, which travel at the same speed (the speed of light) and can travel through a vacuum.

electromotive force (e.m.f.): the voltage across the terminals of a source or the electrical work done by a source (cell, battery, for example) in moving charge around a circuit.

electron: a negatively charged particle, smaller than an atom.

electrostatic charge: a property of an object that causes it to attract or repel other objects with charge.

electrostatic energy: the energy stored when charges are separated or squashed together.

energy: quantity that must be changed or transferred to make something happen.

enlarged: used to describe an image which is bigger than the object.

equilibrium: when no resultant force and no resultant moment act on a body.

evaporation: changing from a liquid to a gas at any temperature.

event: something that happens or takes place, often at a specific time and place.

extension: the increased length of an object (for example, a spring) when a load (for example, weight) is attached to it.

Fleming's left-hand rule: a rule that gives the relationship between the directions of force, field and current when a current flows across a magnetic field.

fluid: a substance which can flow; liquids and gases are fluids.

focal length: the distance from the centre of the lens to its principal focus.

force: the action of one body on a second body; unbalanced forces cause changes in speed, shape or direction.

fossil fuels: material, formed from long-dead material, used as a fuel.

frequency: the number of complete vibrations or waves per second.

friction: the force between two surfaces which may impede motion and produce heating.

fuse: a device that breaks the circuit if the current exceeds a certain value; it is a piece of metal wire that melts when too much current flows through it.

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gamma ray (γ-ray): electromagnetic radiation emitted by an atomic nucleus during radioactive decay.

generator: a device which generates electricity using electromagnetic induction.

geothermal energy: energy stored in hot rocks underground.

gravitational field strength: the gravitational force exerted per unit mass placed at that point.

gravitational potential energy: the energy store of an object raised up against the force of gravity; more generally, it is the distance between particles or bodies.

gravity: the force that exists between any two objects with mass.

half-life: the average time taken for half the atoms in a sample of a radioactive material to decay.

hard (material): a material that, once magnetised, is difficult to demagnetise.

hertz (Hz): the unit of frequency; 1 Hz = 1 wave per second.

image: what we see when we view an object by means of reflected rays.

immerse: to cover something in a fluid (usually water) so that the object is submerged.

incident ray: a ray of light arriving at a surface.

induced e.m.f.: (or induced voltage) the e.m.f. created in a conductor when it cuts through magnetic field lines.

induced magnetism: when a magnetic material is only magnetised when placed in a magnetic field (for example, when brought close to the pole of a permanent magnet).

infrared radiation: electromagnetic radiation with a wavelength greater than that of visible light; sometimes known as thermal energy radiation.

internal (thermal) energy: the energy of an object; the total kinetic and potential energies of its particles.

internal reflection: when a ray of light strikes the inner surface of a material and some of it reflects back inside it.

interstellar cloud: a cloud of gas and dust that occupies the space between stars.

inverted: used to describe an image which is upside down compared to the object.

ionising nuclear radiation: radiation emitted by the nucleus which can cause ionisation: alpha particles, beta particles or gamma rays.

isotope: isotopes of an element have the same proton number but different nucleon numbers.

joule: the SI unit for energy transferred or work done.

kinetic energy: the energy store of a moving object.

kinetic particle model of matter: a model in which matter consists of moving particles.

lamina: flat two-dimensional shape.

laterally inverted: an image in which left and right have been reversed.

light-year: the distance travelled in space by light in one year (it is equivalent to about 9.5×10^{15} m).

limit of proportionality: up to this limit, the extension on a spring is proportional to load.

load: the force (usually weight) that stretches an object (a spring).

longitudinal wave: a wave in which the vibration is forward and back, parallel to the direction of propagation of the wave.

lubrication: usually a liquid, it allows two surfaces to slide past each other more easily.

magnetic field: a region of space around a magnet in which a magnetic pole experiences (feels) a force.

magnetic field lines: represent the direction the magnetic force would have on the north pole of a magnet.

magnetised: when a magnetic material has been made into a magnet.

mass: the quantity of matter a body is composed of; mass causes the object to resist changes in its motion and causes it to have a gravitational attraction for other objects.

melting: changing from solid to liquid.

melting point: the temperature at which a solid melts to become a liquid.

meniscus: curved upper surface of a liquid.

minor planet: an object which orbits the Sun but is not large enough or far enough from another object to be defined as a planet.

model: a way of representing a system which we cannot experience directly.

molecule: two or more atoms joined together by chemical bonds.

moment: the turning effect of a force about a pivot, given by force × perpendicular distance from the pivot.

motor effect: when current flows in a wire in a magnetic field which is not parallel to the current, a force is exerted on the wire.

national grid: the system of power lines, pylons and transformers used to carry electricity around a country.

negative charge: the type of electric charge carried by electrons.

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neutral: having no overall positive or negative charge.

neutron: an uncharged particle found in the atomic nucleus.

neutron star: a collapsed star composed almost entirely of neutrons which forms when a star with more than eight solar masses reaches the end of its life.

non-renewables: an energy resource that is gone forever once it has been used.

normal: the line drawn at right angles to a surface at the point where a ray hits the surface.

north pole (N pole): the end of a magnet which is attracted to the Earth's North Pole.

nuclear energy: energy stored in the nucleus of an atom.

nuclear fission: the process by which energy is released from nuclear fuels by the splitting of a large heavy nucleus into two or more smaller nuclei.

nuclear fusion: the process by which energy is released when two small light nuclei join together to form a new heavier nucleus.

nucleon: a particle found in the atomic nucleus; a proton or a neutron.

nucleon number (A): (or mass number) the number of nucleons (protons and neutrons) in an atomic nucleus.

observations: what you see happening in an experiment.

ohm (Ω): the SI unit of electrical resistance.

orbital period: the time taken for a planet to complete one full orbit of the Sun.

orbital radius: the average distance of the planet from the Sun.

oscillation: a repetitive motion or vibration.

parallel: in a parallel circuit, components are connected in separate loops.

pascal (Pa): the SI unit of pressure, equivalent to one newton per square metre; $1\ \text{Pa} = 1\ \text{N/m}^2$.

period: the time for one complete oscillation or wave; the time it takes an object to return to its original position.

permanent magnet: magnetised magnetic material that produces its own magnetic field that does not get weaker with time.

pivot: the fixed point about which a lever turns; also known as the fulcrum.

plane mirror: (or a flat mirror) a mirror with a flat, reflective surface.

planet: large spherical object that orbits the Sun without another similar object close to it.

planetary nebula: a bubble of gas surrounding a white dwarf star that used to be the outer shell of a red giant from which it collapsed.

plasma: a completely ionised gas in which the temperature is too high for neutral atoms to exist so it consists of electrons and positively-charged atomic nuclei.

plotting compass: very small compass with a needle that lines up with magnetic field lines, allowing changes in field direction to be observed and plotted over a very short distance.

plumb bob: a mass hanging from a string to define a vertical line.

positive charge: the type of electric charge carried in the nucleus of an atom.

potential difference (p.d.): the work done by (a unit) charge passing through an electrical component; another name for the voltage between two points.

power: the rate at which work is done, or the rate at which energy is transferred.

power line: cable used to carry electricity from power stations to consumers.

precise: when several readings are close together when measuring the same value.

pressure: the force acting per unit area at right angles to a surface.

primary coil: the input coil of a transformer.

principal axis: the line passing through the centre of a lens perpendicular to its surface.

principal focus (or focal point): the point at which rays of light parallel to the principal axis converge after passing through a converging lens.

principle of conservation of energy: energy cannot be created or destroyed; it can only be stored or transferred.

principle of moments: when an object is in equilibrium, the sum of anticlockwise moments about any point equals the sum of clockwise moments about the same point.

process: a series of actions or steps, often taking place over a long period of time.

proton: a positively charged particle found in the atomic nucleus.

proton number (Z): (or atomic number) the number of protons in an atomic nucleus.

protostar: a very young star that is still gathering mass from its parent molecular cloud.

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radiation: energy spreading out from a source carried by particles or waves.

radioactive decay: the emission of alpha, beta or gamma radiation from an unstable nucleus.

radioactive substance: a substance that decays by emitting radiation from its atomic nuclei.

random process: a process that happens at a random rate and in random directions; the timing and direction of the next emission cannot be predicted.

rarefaction: a region of a longitudinal wave where the particles are further apart.

ray: a narrow beam of light.

ray box: apparatus used to produce a ray of light.

ray diagram: a diagram showing the path of rays of light.

real image: an image that can be formed on a screen.

red giant: a star that began with fewer than eight solar masses and is burning helium in its core; its shell of hydrogen has expanded and cooled.

red supergiant: similar to red giants, they form when stars with at least eight times the mass of the Sun run out of hydrogen fuel in their core but fusion of hydrogen continues in the outer shells.

reflected ray: a ray of light which has been reflected from a surface.

reflection: the change in direction of a ray or wave when it strikes a surface without passing through it.

refraction: the change in direction of a ray or wave when it passes from one medium to another.

refractive index: the ratio of the speeds of a light wave in two different media.

relative charge: the charge of a particle relative to the charge of a proton.

renewables: an energy resource that will be replenished (replaced) naturally when used.

resistance: a measure of how difficult it is for an electric current to flow through a device or a component in a circuit; it is the p.d. across a component divided by the current through it.

resistor: a component in an electric circuit whose resistance decreases the current flowing.

resultant force: the single force that has the same effect on a body as two or more forces.

right-hand grip rule: a rule which gives the direction of field lines around a straight wire when a current flows through it.

ripple: a small uniform wave on the surface of water.

scalar quantity: is something that has magnitude but no direction.

secondary coil: the output coil of a transformer.

slip rings: a device used to allow current to flow to and from the coil of an a.c. generator.

soft (material): a material that, once magnetised, is easy to demagnetise.

solar cell/photocell/photovoltaic cell: an electrical device that transfers the energy of sunlight directly to electricity, by producing a voltage when light falls on it.

solar panel: used to collect energy that is transferred by light from the Sun.

solenoid: an electromagnet made by passing a current through a coil of wire.

solidifying: changing from liquid to solid.

south pole (S pole): the end of a magnet which is attracted to the Earth's South Pole.

spectrum (plural: spectra): waves, or colours, of light, separated out in order according to their wavelengths.

speed: the distance travelled by an object per unit of time.

speed of light: the speed at which light travels (usually in a vacuum: 3.0×10^8 m/s).

spring constant: the constant of proportionality, the measure of the stiffness of a spring.

stable: an object that is unlikely to topple over, often because it has a low centre of gravity and a wide base.

stable star: a star that is not collapsing or expanding because the inward force of gravity is balanced by radiation pressure, which pushes outwards.

states of matter: solid, liquid or gas.

static electricity: electric charge held by a charged insulator.

step-down transformer: a transformer which decreases the voltage of an a.c. supply.

step-up transformer: a transformer which increases the voltage of an a.c. supply.

supernova: an exploding star that began life with more than eight solar masses and has run out of fuel.

thermal conduction: the transfer of thermal energy by the vibration of molecules.

thermal conductor: a substance that conducts thermal energy.

thermal expansion: the increase in volume of a material when its temperature rises.

thermal insulator: a substance that conducts very little thermal energy.

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total internal reflection (TIR): when a ray of light strikes the inner surface of a material and 100% of the light reflects back inside it.

transformer: a device used to change voltage of an a.c. electricity supply.

transverse wave: a wave in which the vibration is at right angles to the direction of propagation of the wave.

trip switch: safety device that includes a switch that opens (trips) when a current exceeds a certain value.

trough: the lowest point of a wave.

turbine: a device that is made to turn by moving air, steam or water; often used to generate electricity.

turning effect: when a force causes an object to rotate or would make the object rotate if there were no resistive forces.

ultrasound: any sound with a frequency higher than 20 000 Hz.

unmagnetised: when a magnetic material has not been made into a magnet.

unstable: an object that is likely to topple over, often because it has a high centre of gravity and a narrow base.

upright: used to describe an image which is the same way up as the object.

variable resistor: a resistor whose resistance can be changed, for example by turning a knob or moving a slider.

vector quantity: has both magnitude (size) and direction.

velocity: the speed of an object in a stated direction.

vibration (oscillation): a repeated back and forth movement.

virtual image: an image that cannot be formed on a screen.

volt (V): the SI unit of voltage (p.d. or e.m.f.).

voltage: the voltage of a source causes current to flow in a circuit.

voltmeter: a meter for measuring the p.d. (voltage) between two points.

volume: the space occupied by an object.

watt (W): the unit of power when 1 J of work is done per unit time; 1 W = 1 J/s.

wave motion: the transfer of energy without any transfer of matter.

wave speed: the speed at which a wave travels.

wavelength: the distance between two adjacent crests (or troughs) of a wave.

weight: the downward force of gravity that acts on an object because of its mass.

white dwarf: the final stage of a star that started with fewer than eight solar masses after all its fuel has been used up.

work done: the amount of energy transferred when one body exerts a force on another; the energy transferred by a force when it moves: work done = energy transferred.

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