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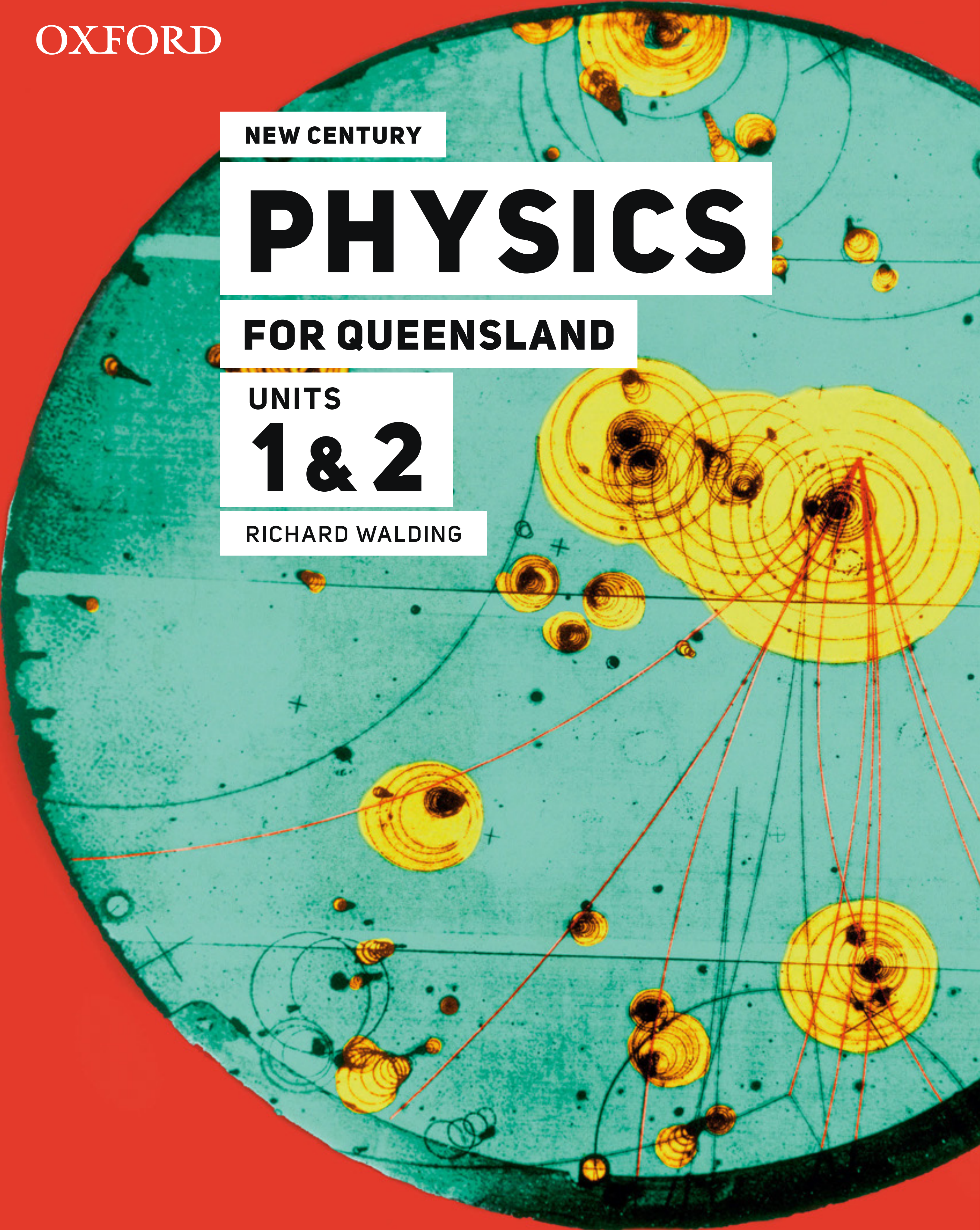
NEW CENTURY

PHYSICS

FOR QUEENSLAND

UNITS 1 & 2

RICHARD WALDING



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OXFORD
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AUSTRALIA & NEW ZEALAND

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Using New Century Physics for Queensland Units 1 & 2

New Century Physics for Queensland Units 1 & 2 has been purpose-written to meet the requirements of the QCAA Physics General Senior Syllabus. The first of a two-volume series, *New Century Physics for Queensland Units 1 & 2* offers complete support for Unit 1 & 2 teachers and their students, providing unparalleled depth and comprehensive syllabus coverage.

Key features of the Student book

Physics toolkit
The Student book begins with a stand-alone reference chapter that includes:

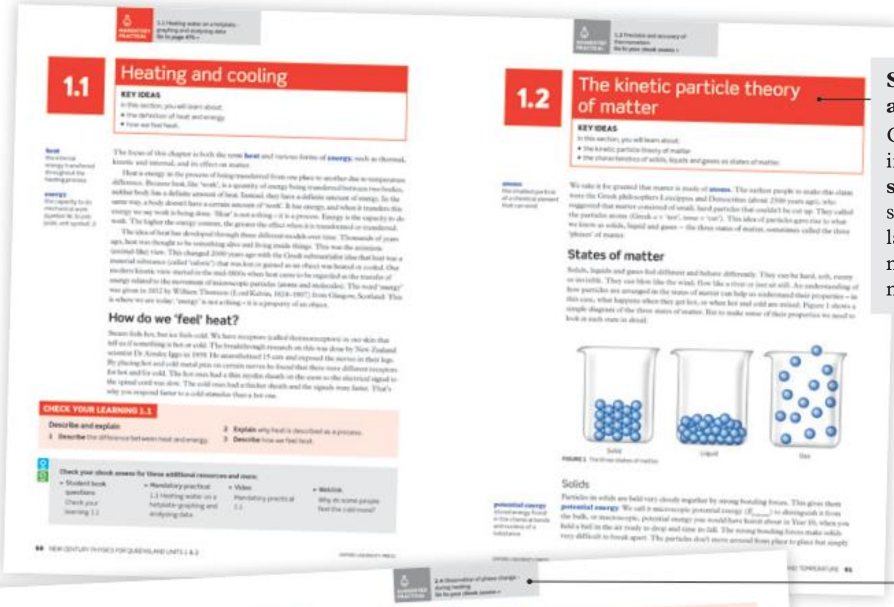
- assessment advice
- a step-by-step guide to preparing for your exam
- methods for presenting and analysing physics data.

Unit openers
Each unit begins with a unit opener that includes:

- an **overview of topics** in the unit
- **unit objectives** from the syllabus.

Chapter openers
Each chapter begins with a chapter opener that includes subject matter from the syllabus.

Practicals
Each chapter opener includes a list of mandatory and suggested practicals from the chapter.



Section-based approach
Content is presented in clearly structured **sections**. Each section is clearly labeled and numbered to help navigation.

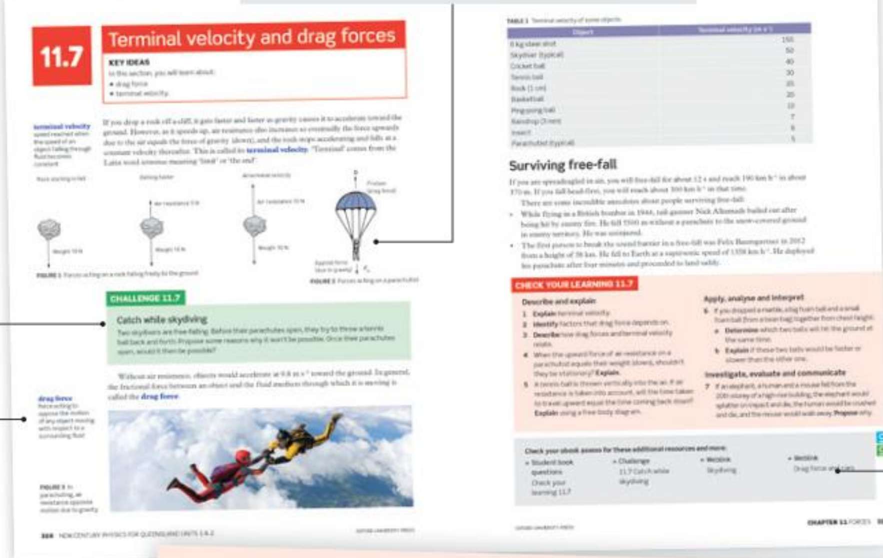
Case studies
Real-life examples illustrate theoretical points being explained in the text.

Practical links
Mandatory and suggested practicals are linked in the relevant section of the Student book.

Study tip
Practical assessment advice helps students improve their performance in assessment tasks.

Science as a human endeavour
Real-world contexts promotes curiosity and can be used as a starting point for research investigations.

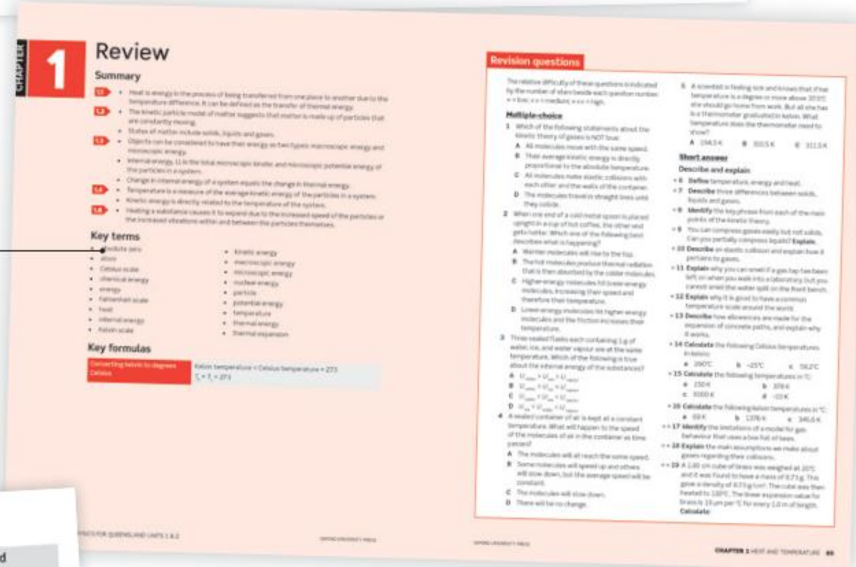
Full-colour diagrams and photos
Rich visual material illustrates concepts and engages students.



Challenges
Scenarios and questions encourage critical thinking.

Margin glossary
Key terms and definitions are highlighted to help students recall important information.

obook assess
Every section includes links to a range of digital resources that support student learning and assessment.



Chapter reviews
Each chapter review includes:

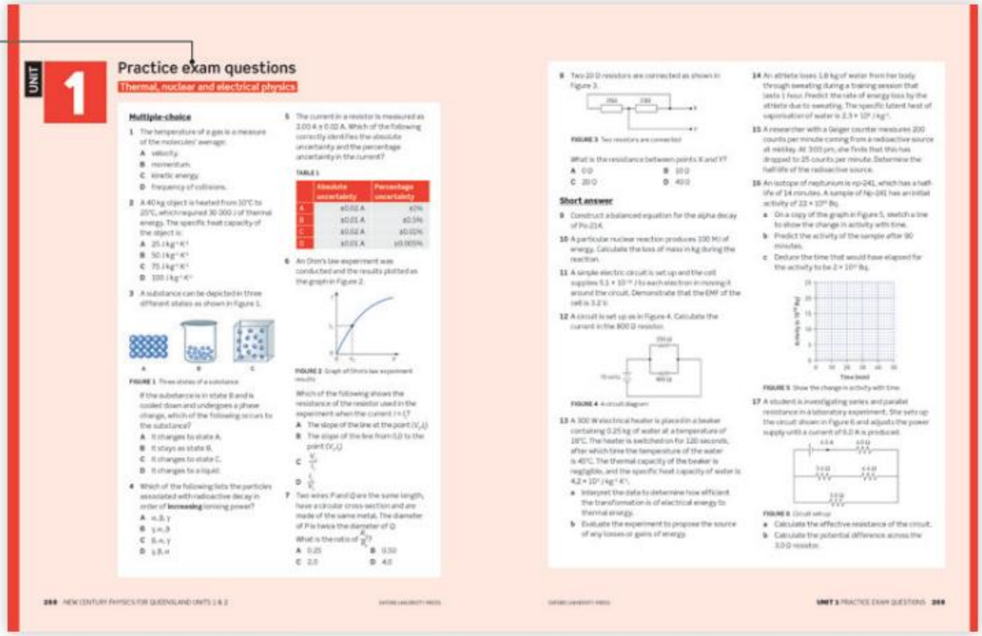
- a **summary of key learning** in each chapter
- **revision questions** written to target assessment through multiple-choice and short-answer questions
- **key terms** introduced throughout the chapter.

Practical manual
Each mandatory practical from the syllabus has **suggested methodologies and materials** included in the practical manual, and suggested practicals are included via obook assess. Each practical is flagged in the relevant section of the Student book.

Practice examination

Each unit includes a set of practice questions to prepare students for their end-of-year external examination. Questions include:

- **multiple-choice questions** to consolidate learning
- **short-answer questions** with additional guidance on how long students should spend on each question.

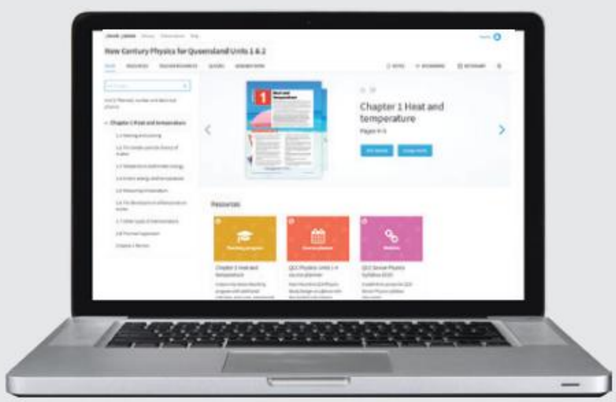


obook assess

New Century Physics for Queensland Units 1 & 2 is supported by a range of engaging and relevant digital resources via obook assess.

Students receive:

- a complete digital version of the Student book with notetaking and bookmarking functionality
- video tutorials demonstrating key skills
- write-in worksheets to accompany all mandatory and suggested practicals
- interactive auto-correcting multiple-choice quizzes
- a range of engaging weblinks to support understanding
- access to work assigned by their teacher: reading, homework, tests, assignments.



In addition to the student resources, teachers also receive:

- detailed planning resources
- Student book answers
- printable (and editable) sample assessments, including data tests and exams with answers
- the ability to set up classes, set assignments, monitor progress and graph results, and to view all available content and resources in one place.

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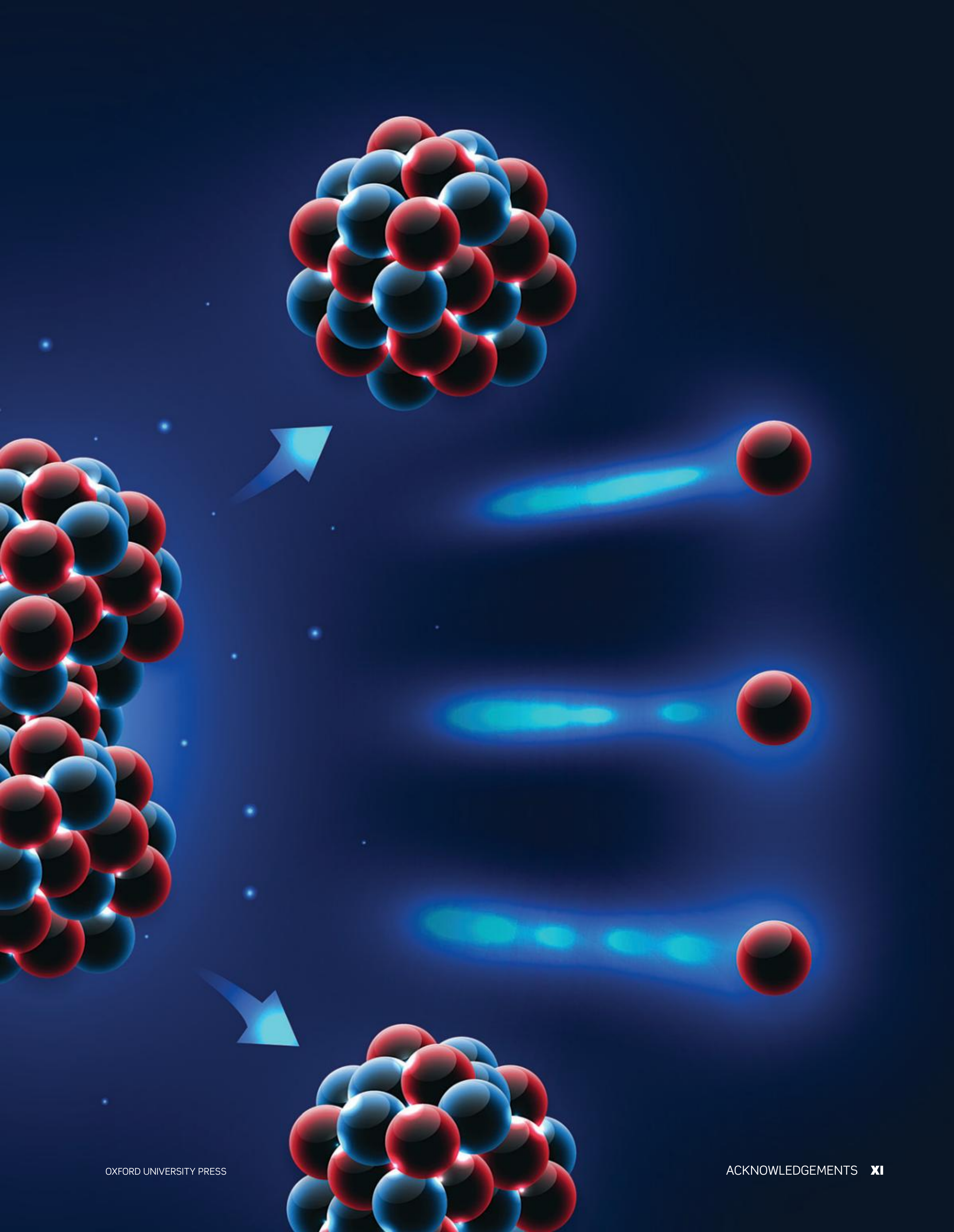

CHAPTER 0

Physics toolkit

Physics, like the other sciences, is all about explaining the natural world. Measurement is at its very heart. Ever since humans have been thinking about their place in the universe, they have been making measurements. There are many different things that humans measure, and therefore there are different types of measurement and different ways of interpreting the measurements taken. As you study physics you will learn about how different questions have been solved. Eventually you will ask your own questions and make your own measurements.

This chapter is called the zeroth chapter to commemorate a highpoint in the history of physics. The zeroth law of thermodynamics is called the 'zeroth' law because it was developed after the first and second laws of thermodynamics had already been proposed and named, but was considered more fundamental and thus was given a lower number – zero. Just like this chapter.

OBJECTIVES

→ Use digital and other measuring devices to collect data, ensuring measurements are recorded using the correct symbol, SI unit, number of significant figures and associated measurement uncertainty (absolute and percentage); all experimental measurements should be recorded in this way.

Source: *Physics 2019 vl.2 General Senior Syllabus © Queensland Curriculum & Assessment Authority*

FIGURE 1 Physicists use calipers to attain accurate measurements.

MAKES YOU WONDER

In this chapter you will learn about the different ways physics makes measurements and interprets these measurements, and answer questions such as:

→ What would have been the first sort of measurement made by humans?

→ Why did they call it the Kelvin temperature scale when William Thomson invented it?

→ What is the shortest length of time that can exist? Is there no limit?

→ Time passes, but why can't it go backwards?

→ Just how heavy is the universe? How did scientists weigh it?

→ Is cream more dense than milk? Who came up with the concept of density?

0.1 What is physics?

KEY IDEAS

In this section, you will learn about:

+ what physics is
+ what a physicist does.

What is physics about?

Physics is the study of our amazing and strange universe and how it works.

A study of energy and matter

Physics is fundamentally concerned with energy and matter, and how they interact with each other. It deals with energy in the form of heat, radiation, electricity, motion, sound, light, magnetism and gravity – how it is transferred and transformed. Physics deals with matter on scales ranging from tiny subatomic particles to stars to galaxies to the edge of the universe and beyond.

An experimental science

Physics is not just about observing the universe. It is an experimental science – it measures and probes the world to formulate and test hypotheses. The results of these experiments are used to formulate models, laws and theories (usually expressed mathematically), and this allows us to predict other phenomena. However, models and laws are not unchanging – the ideas are quite dynamic. Some models used in physics a decade ago have been modified or discarded as new information and understandings have become known. Others have been around for a century or more and have not changed.

A practical science

Physics doesn't just deal with theoretical ideas. It has a practical role in nearly every sphere of human activity, including:

- development of sustainable and efficient forms of energy production
- treatment of cancer through the selection of appropriate radioisotopes for medical imaging and treatment
- predicting and responding to climate change
- provision of a reliable electricity supply and advances in superconductivity
- biomechanics and the understanding of athletic performance
- monitoring earthquakes and tsunamis
- reducing noise pollution by acoustic design
- provision of satellites for weather, traffic and military uses.

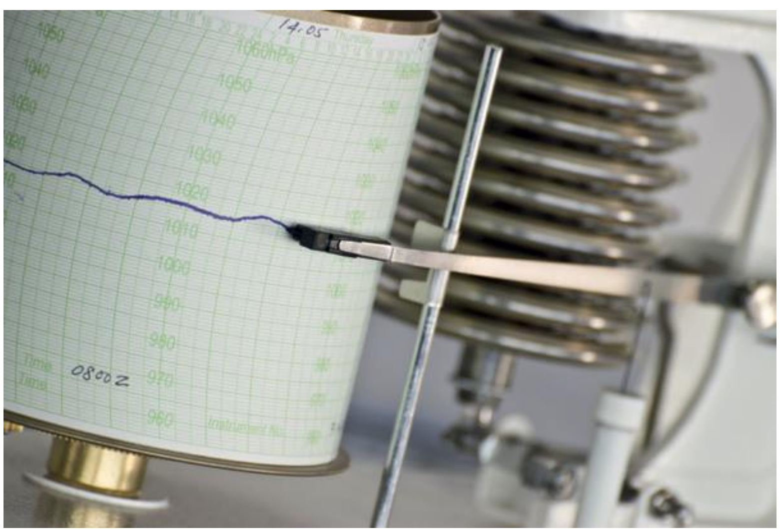

FIGURE 1 Physics has a role in monitoring earthquakes and tsunamis.

A theoretical science

Physics is also called upon to answer some of the most fundamental questions about human existence. The top 10 questions people ask repeatedly, and which physics tries to answer, are:

- What's out there?
- What's the universe made of?
- Are we alone?
- How did it all start, and when?
- How will it end?
- Why is the universe in three dimensions? Is this by accident?
- Can we travel backwards in time?
- If forces attract and repel, can you have antigravity?
- If matter makes up only a small bit of the universe, what's the rest?
- What's the smallest thing you can see – is it a quark?

What do physicists do?

It is surprising what physicists do. A simple answer is 'they do physics'.

Develop technology

Many physicists are researchers, working to find answers to the types of questions listed above. Their answers often lead to unexpected technological applications. For example, all the technology we rely on today, including computers, mobile phones and the internet, is based on a theoretical understanding of electricity developed over a century ago.

Problem-solve

Whether physicists are researchers or work in industry developing new products, they all problem-solve. They take a situation and apply their knowledge and understanding of physics principles, models and laws to improve on what has been done before. Physicists are also the ones who say to manufacturers who ask for their product to be made faster, cheaper and safer, 'You can only choose two of those'. A physicist will often be the one to remind others that you can't break the laws of thermodynamics. They can give sound advice.

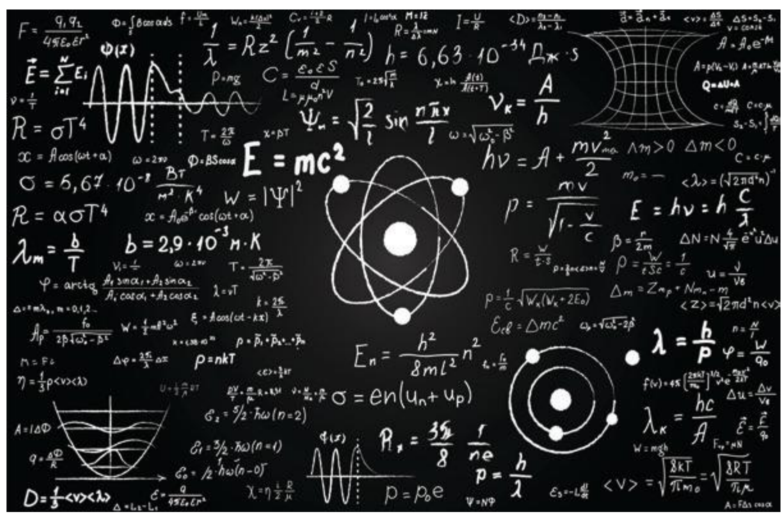

FIGURE 2 Physicists are constantly trying to more precisely define the most fundamental measurable quantities in the universe.

Work in diverse industries

Giving sound advice is why physicists are sought after in a range of diverse industries. Research and planning, analysis of evidence, interpretation and evaluation, and being able to communicate their findings are skills that see physicists employed in a range of unexpected workplaces.

Physicists don't all work in research laboratories – they work in places such as museums, the military, teaching in high schools, lecturing at universities, in hospitals, power generation and distribution companies, the IT industry, astronomical and meteorological observatories, in law firms, the finance sector, engineering firms and in businesses. Physicists generally have outstanding analytical, mathematical and critical thinking abilities – characteristics that are worthwhile no matter which industry they are employed in.

Face challenges

One of the biggest ongoing challenges for research physicists is to more precisely define the most fundamental measurable quantities in the universe, ranging from the gravitational constant to the mass of a neutrino. The effort to find the most fundamental description of the universe has always been a big part of physics research and will continue to be while physics exists. Physicists try to understand the relationships between those fundamental quantities and develop laws about conservation of energy and the speed limit of the universe. These relationships are expressed using models, graphs, words, equations and diagrams in a way that helps us make sense of things.

Physics is the study of this truly amazing and strange universe and, more importantly, how it works.

CHECK YOUR LEARNING 0.1

Describe and explain

1 **Define** 'physics' in 10 words or less.

2 **Recall** whether physicists can work in finance and business sectors.

Apply, analyse and interpret

3 **Distinguish** between 'problem-solving' and 'developing technology' as applied to the use of physics.

4 **Interpret** the statement that 'physics is a practical science'. Does it mean that all research has to have a practical outcome like saving energy or making more powerful satellites?

5 **Judge** whether this is true: 'Physics is said to be an experimental science so all physics theories have to come from experiments'.

Investigate, evaluate and communicate

6 **Propose** a response to this question from a friend: 'How can they say the Big Bang really occurred when no one was there?'

7 **Propose** how physics might be used in chemistry and biology; and how physics relies on mathematics.

OI

Check your obook assess for these additional resources and more:

» Student book questions
Check your learning 0.1

» Video
What does a physicist do?

» Weblink
QCAA Physics General Senior Syllabus

» Weblink
Physicists in action

0.2 Physical quantities

KEY IDEAS

In this section, you will learn about:

+ prefixes used in physics
+ the International System of Units, SI (Système international d'unités)
+ converting from one unit to another.

There are a number of things in the world we want to measure. As well as length, time and mass, people are interested in measuring temperature, electric current and weight. These measurable features are called physical quantities.

SI units

The International System of Units called SI (from the French name for the system, Système international d'unités) is now commonly used around the world. It is often called the metric system (from the Greek *metron* = 'measure').

The seven fundamental (base) units of this system are shown in Table 1.

TABLE 1 The seven fundamental units of the Système international d'unités

Physical quantity	Symbol of quantity	Name of unit	Symbol for unit
Length	l	metre	m
Mass	m	kilogram	kg
Time	t	second	s
Electric current	I	ampere	A
Temperature	T	kelvin	K
Amount of substance	n	mole	mol
Luminous intensity	I_v	candela	cd

Prefixes

To obtain multiples of the base units, prefixes are added. Table 2 lists some of the prefixes that will be used throughout your physics course. You should memorise these from nano to mega.

TABLE 2 Prefixes for units and their symbols

Prefix	Symbol	Meaning	Value	Factor
femto	f	one billion-millionth	0.000 000 000 000 001	10^{-15}
pico	p	one million-millionth	0.000 000 000 001	10^{-12}
nano	n	one thousand-millionth	0.000 000 001	10^{-9}
micro	μ	one millionth	0.000 001	10^{-6}
milli	m	one thousandth	0.001	10^{-3}
centi	c	one hundredth	0.01	10^{-2}
deci	d	one tenth	0.1	10^{-1}
kilo	k	one thousand	1000	10^{3}
mega	M	one million	1000 000	10^{6}
giga	G	one thousand million	1000 000 000	10^{9}
tera	T	one million million	1000 000 000 000	10^{12}

Example of using a prefix with a unit: 1 millimetre = 10^{-3} metre = 0.001 metre.

Derived units

New quantities can be made up of the base quantities. These are called derived quantities. For example, you can have combinations of the base units (such as metres per second and cubic metres) or you can have derived quantities that have been given specific names (such as newton, coulomb and watt).

TABLE 3 Derived units

Derived quantity	Unit	Symbol for unit
Acceleration	metre per second squared	$m\ s^{-2}$
Angle	radian	rad
Area	metre squared	m^2
Capacitance	farad	F
Density	kilogram per metre cubed	$kg\ m^{-3}$
Electric charge	coulomb	C
Energy	joule	J
Force	newton	N
Frequency	hertz	Hz
Momentum	kilogram-metre per second	$kg\ m\ s^{-1}$
Potential difference	volt	V
Power	watt	W
Pressure	pascal	Pa
Resistance	ohm	Ω
Velocity	metre per second	$m\ s^{-1}$
Volume	metre cubed	m^3

Converting units

It is important to know how to convert from one SI unit to another (for example, from millimetres to metres). This is needed when data is given in one particular unit but the answer has to be given in another form. This might occur when some constant is involved that is in a unit different from that of the data given. For example, if you had to calculate how far you would travel in 10 minutes at a speed of 5 metres per second, you would convert 10 minutes to seconds (10 × 60 = 600 seconds) and multiply this number of seconds by the speed (600 × 5 = 3000 metres).

Some other simple conversion examples are:

25 000 cm = 250 m (2.5×10^2 m)

23 km = 23 000 m or 2.3×10^4 m

6 hours = 21 600 s or 2.16×10^4 s

FIGURE 1 Measuring length, time, mass, temperature, electric current and weight is a fundamental part of physics.

WORKED EXAMPLE 0.2

Imagine you have made measurements of a block of wood in a density experiment and need to calculate its volume in cubic metres. Length 35 cm, depth 2.0 cm, width 1.5 cm.

SOLUTION

Step 1: Convert the measurements to SI units (metres):

Length = 35 cm = 35 × 1 × 10^{-2} m = 0.35 m (3.5 × 10^{-1} m)

Depth = 2.0 cm = 2.0 × 1 × 10^{-2} m = 2.0 × 10^{-2} m

Width = 1.5 cm = 1.5 × 1 × 10^{-2} m = 1.5 × 10^{-2} m

Step 2: Calculate the volume:

Volume = 0.35 m × 2.0 × 10^{-2} m × 1.5 × 10^{-2} m = 1.05 × 10^{-4} m^3.

CHALLENGE 0.2

Use of newtons in physics

Explain in 50 words or less why we use newtons instead of pounds in physics.

CHECK YOUR LEARNING 0.2

Describe and explain

1 **Identify** the seven fundamental SI quantities and their quantity symbols.

2 Word list: yard, luminous intensity, ampere, year, minute, temperature, force, second, pressure
Apply your understanding of the quantities in the word list to select:
- a two fundamental quantities
- b two fundamental units
- c two non-SI units.

3 **Calculate** the following conversions:
- a 10.3 m to cm
- b 1120 cm to m
- c 1.8 mm to m
- d 4.8 cm^3 to m^3.

Apply, analyse and interpret

4 **Distinguish** between the SI symbols for time and temperature.

5 **Determine** the speed of light (3 × 10^8 m s^{-1}) in:
- a km h^{-1}
- b kilometres per second.

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SI

0.3 Scientific notation

KEY IDEAS

In this section, you will learn about:

+ scientific notation.

Things are not always human-sized. Some are very small and some are huge. The numbers used to express these measurements can get messy. For example, the time taken for light to travel from one side of an atom to the other is about one billion, billion, billion, billionth of a second. The mass of the Sun is two thousand billion, billion, billion kilograms.

In his book *A Brief History of Time*, Stephen Hawking mentioned that the publisher told him not to use any numerals. It was argued that all numbers had to be spelt out because people couldn't understand exponents and wouldn't buy a book with them in it. Because of this, the speed of light appears in his book as three hundred million metres per second.

The time after the Big Bang that it took for electrons to be created was a thousand billion, billion, billion, billion, billionths of a second. There is a simpler way of expressing these values.

A shorthand way of expressing such numbers is called exponential notation. For example:

- 1 million (1 000 000) is written as 10^6
- 1 billion (1 000 000 000) is written as 10^9
- 1 millionth (1/1 000 000 or 0.000 001) is written as 10^{-6}
- 1 billionth (1/1 000 000 000 or 0.000 000 001) is written as 10^{-9}.

Exponents tell us how many times 10 must be multiplied together and hence give the number of zeros. The expression 10^3 means 10 multiplied by itself three times ($10 \times 10 \times 10$) – in other words, 1 with three zeros following it (1000).

scientific notation
a shorthand way of expressing very large or very small numbers in terms of a decimal number between 1 and 10 multiplied by a power of 10

When writing numbers using exponents, it is common practice to use **scientific notation**. This involves the following conventions:

- Write numbers in exponential notation with just one numeral before the decimal point. For example, the Earth–Moon distance of 382 million metres could be expressed as 382×10^6 m or in scientific notation as 3.82×10^8 m.
- Leave numbers between 0.1 and 100 as they are. There is no need to express 60 seconds as 6.0×10^1 s.

WORKED EXAMPLE 0.3

Write the following in scientific notation:

a the speed of light: three hundred million metres per second.

b the diameter of a red blood cell: 2 millionths of a metre (0.000 002 m).

SOLUTION

a Three hundred million is 300×10^6, so the speed of light can be written as 3.00×10^8 m s^{-1}.

b 0.000 002 m is written as 2×10^{-6} m.

With scientific notation, only one numeral appears before the decimal place. The exponent has to be adjusted to allow for this. For example, when the number 300×10^6 became 3.00×10^8, the decimal point in 300 was shifted two places to the left (made smaller) to become 3.00. To compensate, the exponent must be increased by two units from 10^6 to 10^8 (made bigger).

Negative exponents are used to indicate numbers less than 1. For example, an electron has a mass of 0.000 549 units. To make this 5.49 we have to shift the decimal point four places to the right (make it bigger by 10 000), so an exponent has to be included that compensates for this. In scientific notation the mass of an electron would be 5.49×10^{-4} units.


FIGURE 1 Stephen Hawking was initially asked to avoid using numerals when writing *A Brief History of Time.*

Further examples of scientific notation:

- The radius of Earth is 696 million metres or 6.96×10^8 m.
- The diameter of Saturn is 120 thousand kilometres or 1.20×10^5 km.
- The diameter of an atom is 0.000 000 000 1 m or 1×10^{-10} m.

Significant figures

Scientists imply the level of uncertainty in measurements by how they report the number. You will see later that we can state a measurement in three parts: the best estimate, the uncertainty and the unit. For example, when we say 'length = 25.0 ± 0.5 mm', we mean that the reading could be between 24.5 and 25.5 mm. However, if we just say the measurement is 25.0 mm and don't state the (±) uncertainty, we are saying that it is somewhere between 24.9 and 25.1 mm. We have used three figures that are significant (the 2, the 5 and the 0) to say this. Unlike in mathematics, where 25 and 25.0 are identical, a measurement of 25 cm in science means something different than a measurement of 25.0 cm. The key principle is that scientific measurements are reported to one digit more than what is known with certainty.

A reported value of 25 cm implies that the actual value is somewhere between 24 cm and 26 cm, approximately. In contrast, a reported value of 25.0 cm implies that the actual value is somewhere between 24.9 cm and 25.1 cm, approximately. The measurement 25 cm is said to have two **significant figures**, whereas 25.0 has three significant figures.

You must be able to work out how many significant figures are in a result (these are shown in **bold)**.

Rules:

- All non-zero figures are significant: **3.18** has three significant figures (3 sf).
- All zeros sandwiched between non-zeros are significant: **30.08** has 4 sf.
- Zeros to the right of a non-zero figure but to the left of the decimal point are not significant (unless specified with a bar): **109** 000 has 3 sf (the 109). The rest just indicate where the decimal place is. If you wanted to show that the second zero from the right is significant, you could write $109\,0\overline{0}0$ (5 sf).
- Zeros to the right of a decimal point but to the left of a non-zero figure are not significant: 0.0**50** has 2 sf. Only the last zero is significant. The first zero merely says where the decimal point is.
- Zeros to the right of the decimal point and following a non-zero figure are significant: **304.50** has 5 sf.

Study tip

It is much easier to write numbers in scientific notation if you want to show significant figures. Everything in a number written in scientific notation is significant. If it is not significant, you just leave that number out.

significant figures
the digits of a number that are used to express it to the required degree of accuracy (abbreviated: sf)

Some examples of the application of these rules are given in Table 1.

TABLE 1 Examples of scientific notation

Number	Number of significant figures	Scientific notation
0.0035	2	3.5×10^{-3}
0.003 50	3	3.50×10^{-3}
0.35	2	3.5×10^{-1}
3.5	2	$3.5\ (\times 10^{0})$
3.50	3	$3.50\ (\times 10^{0})$
35	2	3.5×10^{1}
350	2	3.5×10^{2}
3500.0035	8	$3.500\,003\,5 \times 10^{3}$

Note: normally, numbers between 0.1 and 100 are not written in exponential form, but some are shown here for clarity.

Calculating with significant figures

A problem arises when performing calculations using significant figures, so you need to be careful.

Multiplying and dividing

Imagine you had to calculate the surface area of a road going through prime agricultural land. The traffic engineers said the road easement would be 95.5 m wide and 26 km long. When multiplying 95.5 m × 26 000 m, the answer would appear to be 2 483 000 m^2. When multiplying or dividing, the answer should contain only as many significant figures as the number in the operation that has the least number of significant figures. In this case, 95.5 m has three significant figures and 26 000 m has two. The answer should only have two significant figures, so it should be written as 2 500 000 m^2 or 2.5×10^6 m^2.

Other examples:

- 45.71 (4 sf) × 34.1 (3 sf) = 1558.711. This is rounded to 1560 or 1.56×10^3, which has three significant figures (3 sf).
- 365 (3 sf) ÷ 2.4 (2 sf) = 152.083 333 3. This is rounded to 150 or 1.5×10^2 (2 sf).

Rounding

You should only round to the correct number of significant figures at the end of your calculations. Leave in your calculator (or write down) as many decimal places as you like during your calculations, and then adjust at the very end. When you have an answer in your calculator that has 11 decimal places, you shouldn't write them all down – you must round them off.

- Numerals lower than 5: round off to zero.
- Numbers larger than 5: round off to 10.
- When the number to be rounded is 5: take it up to 10 if the number preceding is even, otherwise take it down to zero.

For example, when 16.586 is rounded to four significant figures it becomes 16.59. When 24.65 is rounded to three significant figures it becomes 24.7 (as the 6 is even and hence the 5 is rounded up to 10).

Addition and subtraction

If a 2.55 g bullet strikes a 1575 g target and becomes embedded in it, the mass of the target is now 1575 g + 2.55 g = 1577.55 g. Or is it? The final mass has more significant figures than either the target's mass or the bullet's mass. Intuitively, this should sound wrong. The final mass should be written as 1578 g. Calculations are rounded to the least significant **decimal place value** in the data. Decimal place is sometimes shortened to dp.

Examples:

- 264.68 (2 dp) – 2.4711 (4 dp) = 262.2089 = 262.21 (rounded to 2 dp).
- 2.345 (3 dp) + 3.56 (2 dp) = 5.905 = 5.91 (rounded to 2 dp).

CHECK YOUR LEARNING 0.3

Describe and explain

1 **Explain** the purpose of using scientific notation.

2 **Calculate** the following:
   a $(1.2 \times 10^{-3}) \times (2.2 \times 10^{-4})$
   b $(1.8 \times 10^{3}) \div (6.4 \times 10^{-8})$

3 **Identify** the number of significant figures in each of the following, and then write each in scientific notation using the correct number of significant figures:
   a 100.010
   b 1999
   c 2.222 2
   d 40 000

4 **Calculate** the following:
(2.34 kg + 1.118 kg) ÷ (1.05 cm × 22.2 cm × 0.9 cm).

Apply, analyse and interpret

5 **Determine** which is larger: 1.5×10^{-4} or 0.001 50.

6 **Apply** rules to express the following in scientific notation:
   a 3558.76
   b 40.00
   c 79 000
   d 200 326

7 **Calculate** the volume of an atom of diameter 0.000 000 001 m. $\left(V = \frac{4}{3}\pi r^3\right)$

8 A sheet of copper was measured as part of a density experiment. The dimensions were: length = 55.5 cm, breadth = 2.0 cm, thickness = 0.02 cm. **Determine**:
   a the area of the largest surface
   b the volume
   c the perimeter of the largest face.

9 Earth is approximately a sphere of radius 6.37×10^{6} m. **Determine** its:
   a circumference
   b volume in cubic metres
   c volume in cubic kilometres.

Investigate, evaluate and communicate

10 Isaac Asimov proposed a unit of time based on the highest known speed of light and the smallest measurable distance. The light-fermi is the time taken by light to travel a distance of 1 fermi (= 1 femtometre = 1 fm = 10^{-15} m).
Determine how many light-fermis there are in 1 second. Recall that light travels at 3×10^{8} m s^{-1}.

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0.4 Errors and error analysis

KEY IDEAS

In this section, you will learn about:

- uncertainty
- systematic errors
- random errors
- scale reading limitations.

precision
the uncertainty of the measurement

accuracy
the difference between the measured value and the true or accepted value of the observed quantity

A part of any physics experiment is to record and analyse your measurements for quality. This is called an error analysis. The word 'error' is a rather vague term about the 'goodness' of your observations, but specifically refers to the **precision** and **accuracy** of your results.

Precision and accuracy mean vastly different things, so it is important that they are used correctly. We can say that for a set of measurements:

- **Precision** is the range of values found; that is, the *uncertainty* of the measurement.
- **Accuracy** is the difference between the measured value and the true or accepted value of the observed quantity.

We will consider these in the order met in an experimental report.

Uncertainty

If you had to count the number of wires in a cable, such as in Figure 1, you would obtain an exact figure. However, if you had to measure the width of the cable with a ruler, your measurement would be an approximation (probably to the nearest millimetre). This is where problems start in experimental physics.

You may have learnt that measurements (data) can be:

- discrete (numeric) – such as numbers of wires, swings of a pendulum or layers of metal foil
- continuous (any value over a continuous range) – such as the diameter of a wire, the mass of an object or a thermometer reading
- categorical (types) – such as positive/negative, red/green/blue (quarks), up/down, kinetic/ potential (energy).

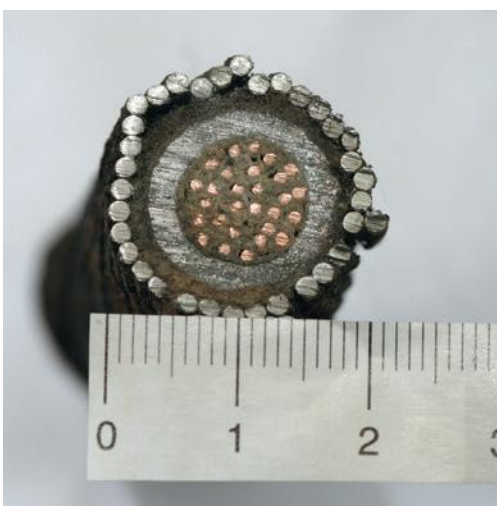

FIGURE 1 An old power cable – it is easy to count the number of wires, but it is hard to measure the diameter.

Experiments in high school physics are full of measurements that are continuous. Unlike discrete measurements (whole numbers), continuous measurements can never be exact because they all have some amount of uncertainty.

Uncertainty is inevitable, so you should use it to your advantage. Showing that you understand uncertainty is the key to top marks in experimental reports and data analysis.

What causes uncertainty?

Uncertainties are also called errors. In science, you can use the words interchangeably, which is a problem. People tend to think of errors as mistakes, but they are not – particularly in error analysis. 'Error' comes from the Latin word meaning 'wandering'. Errors are wanderings in the data – the data is all over the place. These errors are always due to either humans or the instrument(s) used in the experiment.

There are three types of errors that contribute to the uncertainty of our result:

- systematic errors
- random errors
- mistakes.

Mistakes are not really experimental errors – they are just mistakes that happen during an experiment. A person may record a wrong value, misread a scale (such as amps instead of milliamps), forget a digit when reading a scale or recording a measurement, or similar. Blunders happen, even to experienced scientists, and should not be included in the analysis of data. If you misread a scale by miscalculating the value of each division you have made a 'scale reading error', but it is really just a mistake.

There are two important types of real errors found in experimental work:

- systematic errors
- random errors.

FIGURE 2 A mistake can be recording a wrong value or misreading a scale.

Systematic errors

You can end up with **systematic errors** in a measurement because of problems with the measuring instrument or the conditions under which it was made. For example, a scale may be incorrectly calibrated during manufacture or become warped or damaged over time. Measuring tapes may become stretched with time. A stopwatch can run slow if the timing chip has a fault.

They are called systematic errors because it is the system being used that causes the problem. Such errors usually occur to the same extent in each one of a series of measurements. They can be identified, and corrections can then be made. The best definition is:

Systematic errors are errors affected by the accuracy of a measurement process that causes readings to deviate from the accepted value by a consistent amount each time a measurement is made.

Let's look at some of these systematic errors and how to manage them.

systematic errors those that cause readings to deviate from the accepted value by a consistent amount and in the same direction each time a measurement is made. They are affected by the accuracy of a measurement process

Zero error

A zero error occurs when the instrument has not been correctly set to zero before commencing the measuring procedure. For instance, an ammeter may show a reading of 0.05 A when no current is flowing (Figure 3). As you use this ammeter to measure various currents, each of your measurements will be in error by 0.05 A.

Another example of a zero error is where the end of a ruler is not on the zero mark to start with.

Managing zero errors

In the case of the ammeter in Figure 3, the needle can be reset to zero by using the adjusting screw before the measurements are taken.

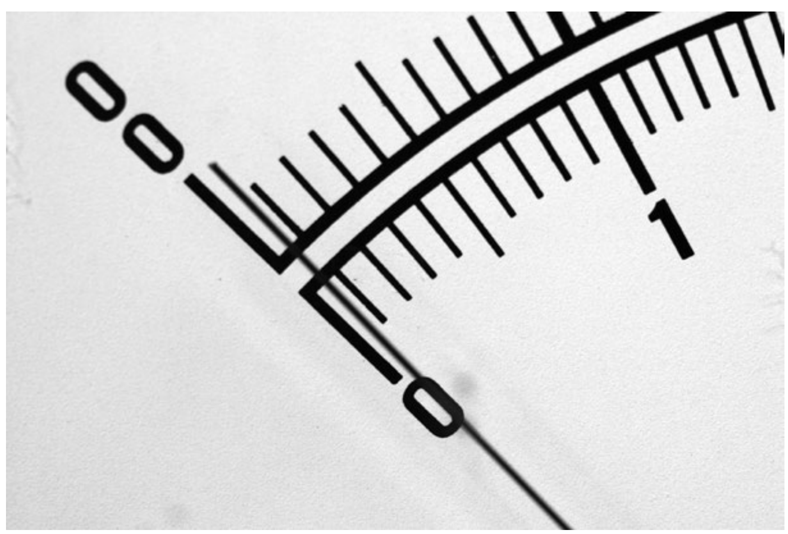

FIGURE 3 Zero error of 0.05 A, which can be corrected by adjusting the pointer with a screwdriver

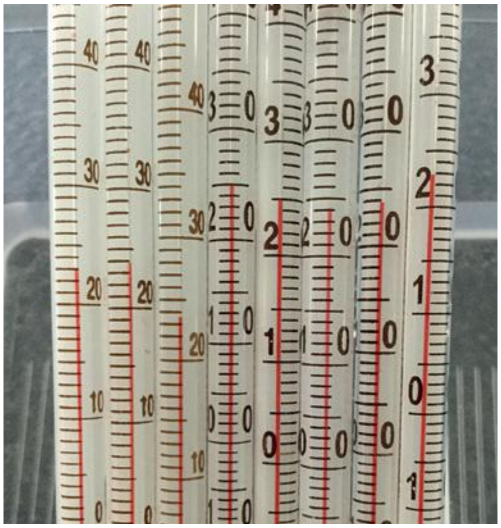

FIGURE 4 Eight thermometers placed in a beaker of water for 10 minutes don't all read the same as they are not well calibrated.

Calibration error

A calibration error occurs when there is a difference between the value indicated by an instrument and the actual value. Examples include a stopwatch that consistently runs fast or slow and a thermometer that is badly calibrated.

Figure 4 shows eight thermometers placed in a beaker of water for 10 minutes. Have a look at all the different readings. They are not that well calibrated. It is a calibration error, which is an error you can allow for.

Managing calibration errors

Check that an instrument is not damaged (warped, bent or stretched) before using it. If there is a known calibration error, the device can be labelled with the correction you have to make to the scale reading.

Parallax error

A parallax error occurs when you view the scale of a measuring instrument at an angle rather than from directly in front of it (perpendicular to it), therefore using the instrument wrongly on a consistent basis. Examples include reading a clock at an angle so that the hand appears to be over another number, reading a ruler at an angle (Figure 5), and reading a thermometer at an angle. If this is done consistently, it introduces a systematic error into the results.

Managing parallax errors

Parallax errors can be avoided by reading the scale with your dominant eye perpendicular to it.

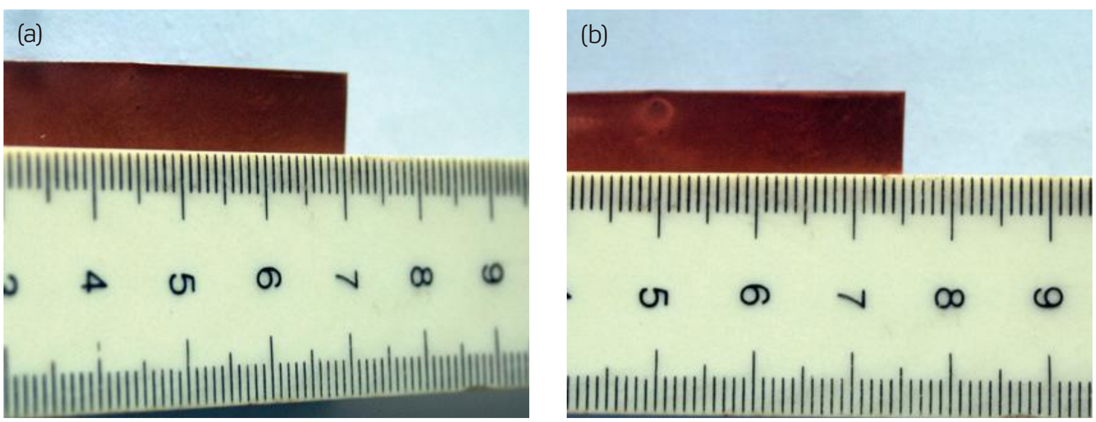

FIGURE 5 (a) Parallax error (looking from the left) reads 7.0 cm. (b) No parallax (eyes directly overhead) reads 7.5 cm.

Reaction time

Reaction time is the time taken for a person or a system to respond to a certain event. Although it is only a brief amount of time, reaction time errors need to be accounted for when analysing data.

Managing reaction time errors

An electronic light gate can be used to minimise reaction time errors. Another way is to video an event for later analysis.

Environmental causes

Table 1 is a list of typical systematic errors caused by the environment and ways to correct them.

TABLE 1 Common systematic errors in physics

Cause	Example	Fix
Temperature	A metal rule that has been calibrated for use at 25°C will only be accurate at that temperature. If it is used at another temperature, it will produce readings that are consistently larger than they should be.	Note the experimental temperature and the change in scale reading. Add or subtract as necessary.
Air resistance	This may slow down the motion of a pendulum or a dropped ball. It will never speed the object up, so it is not random, it is a systematic error.	Use an object with a high weight to surface area ratio (e.g. a golf ball over a ping pong ball).
Background radiation	A Geiger counter will register 'counts' even when there is no radioactive specimen in the room. This background radiation comes from rays from the Sun or from gas in bricks and is always there. This will always make the count bigger, so it is a systematic error.	In measuring the count rate of a radioactive specimen, the background radiation should be subtracted.
Background field	Earth's magnetic field will affect magnetism experiments and should be accounted for. It is only a systematic error if it always affects the results in the same direction (higher or lower).	Acknowledge the changes.
Dirt or corrosion	Measuring the diameter of a wire or metal electrode can be a problem if there is rust, corrosion or dirt.	Clean the wire or electrode with steel wool, sandpaper or ethanol.
Unevenness of the object	A piece of wire, fishing line, guitar string or similar will often be 'out of round' or have different diameters at different places along its length.	Make several measurements at the one spot (e.g. 90° to each other) and measure at several places along the wire.

Systematic errors and graphs

Systematic error is the contribution to the uncertainty in a measurement result that is identifiable and quantifiable. For example, zero error, parallax error, calibration error, environmental errors and so on. Systematic errors can drastically affect the accuracy of a set of measurements. Unfortunately, systematic errors often remain hidden.

Often a systematic error can be identified when the data is graphed. If the line of best fit doesn't go through the origin (0,0) when it is expected to (based on theory), there could be a systematic error. For example, the graph of current vs voltage in Figure 6 is taken from an Ohm's law experiment.

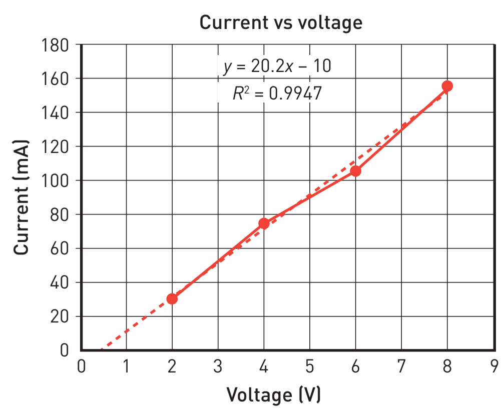

FIGURE 6 Identifying a zero error graphically

For an Ohm's law circuit, it is expected that the current starts to rise as the voltage increases from zero. The projection of the line suggests that the current doesn't start to rise until the voltage is 0.5 V. If the line were extended to the vertical axis (y-axis), when $V = 0$ it would touch the vertical axis at –10 mA. It appears there was a zero error of –10 mA in the ammeter. This is also shown by the 'c' value in the equation for the line. For a zero error of +10 mA, the line would intercept the y-axis at +10 mA. Parallax error would appear the same on these graphs.

Random errors

random errors those due to the limitations (uncertainty) of the measurement equipment and the uncontrollable effects of a method and environment on a measurement result

scale reading limitations the inability of an instrument to resolve small measurement differences

Random errors are two-sided errors because they tend to fluctuate above and below the true value. A common source of these errors is when you try to estimate a quantity that lies between the graduations (the lines) on an instrument such as a metre ruler, thermometer or voltmeter. Sometimes the measurement will be over the true value and sometimes it will be under. Because these errors are random, there will be as many values over as under – they are said to follow a 'Gaussian' (normal) distribution.

One source of random errors is **scale reading limitations** (see below). The best way to handle random errors is to make several repeat readings and then average them.

Identifying random errors

One common way to identify random errors is by examining the data plotted on a graph. The graph in Figure 7 shows data points scattered on both sides of the trend line. This indicates they were random. If the data points were such that the trendline didn't go through the origin (if that is what was expected), it would indicate a systematic error and you would have to look for the source of the error.

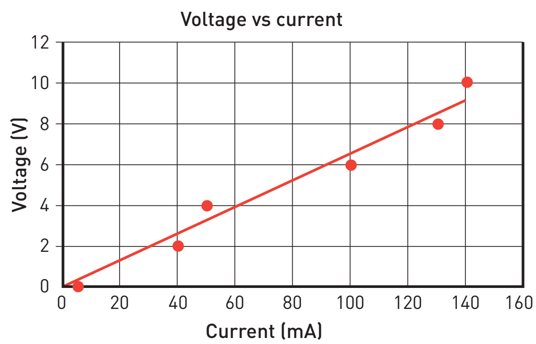

FIGURE 7 Randomly distributed results point to random errors

The R^2 value for this graph is 0.96, which indicates there is a significant amount of random error giving rise to widely scattered points. The closer the R^2 value is to 1.00, the better the line fits the data. With widely scattered points the line has to cut through the middle of them, so the trend line doesn't capture all the points. You should aim for your R^2 value to be over 0.98 if possible.

reliability the ability to be trusted to be accurate or correct, or to provide a correct result

reliable constant and dependable, or consistent and repeatable

Good-quality and well-maintained equipment usually has good **reliability** and produces data that is **reliable**.

Random errors are uncontrollable effects of the measurement equipment, procedure and environment on a measurement result. The magnitude of random error for a measurement result can be estimated by finding the spread of values around the average of independent, repeated measurements of the quantity.

Study tip

Remember, the number must be to the nearest half-scale division (0.5 mm) and the uncertainty is also a half-scale division.

Scale reading limitations

In physics, we usually deal with two types of scales:

- printed (e.g. a ruler, alcohol-in-glass thermometer, analogue voltmeter/ammeter)
- digital (e.g. electronic stopwatch, digital voltmeter/ammeter).

Uncertainty with printed scales

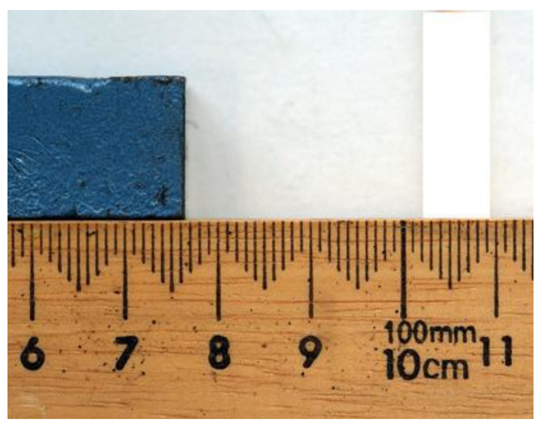

FIGURE 8 To students, the reading here would generally be stated as 76 or 77 mm, but it actually looks closer to 76.5 mm. The best estimate is 76.5 mm with an uncertainty of ±0.5 mm.

The biggest contribution to random errors comes from the limitations of the scale. Students generally read scales to the nearest mark or division. However, we can do better than that.

You should record the **best estimate** and indicate the uncertainty with a plus/minus value to show the range. For a single measurement, the uncertainty is a half-scale division.

How to record results

You should record the result of a measurement in three parts:

1 **best estimate** – read scales to the nearest half-scale division (such as 26.0 or 26.5)
2 **uncertainty** – use ± a half-scale division (such as ±0.5 for a 1°C division)
3 **unit** – (such as °C).

For example, a temperature result could look like this: 26.5 ± 0.5°C.

best estimate
a value closest to the true value, usually found by taking repeated measurements and averaging

Uncertainty with digital scales

How do we determine the uncertainty of digital displays? The Vernier calliper shown in Figure 9 displays a reading of 0.59 mm for the diameter of the nichrome wire. We say the uncertainty is ±0.01 mm. The actual value could be anywhere in the range of 0.58 mm to 0.60 mm.

FIGURE 9 This digital Vernier calliper being used to measure the diameter of nichrome wire can read to one-hundredth of a millimetre. However, closing the jaws with too much force can result in quite significant errors.

Summary of the limitations of measuring instruments

- Uncertainty in a scale measuring device is equal to a half-scale division.
- Uncertainty in a digital measuring device is equal to the smallest increment.

CHECK YOUR LEARNING 0.4

Describe and explain

1 **Explain** the meaning of the following: systematic error, random error, scale reading uncertainty, zero error, calibration error, parallax error, mistake.

2 Some voltmeters in a class had zero error problems. It seemed to be random as to which ones had this error and which didn't. **Explain** why zero error is considered a systematic error rather than a random error.

Apply, analyse and interpret

3 **Differentiate** between the scale reading uncertainty for an analogue (printed) scale and a digital scale.

4 The meters in Figure 10 are all reading the voltage across the same resistor.
 a **Determine** the best estimate and the uncertainty for each meter reading.
 b **Classify** the sort of error that the meters are displaying.

5 **Deduce** which of the following voltage measurements is the most precise: $V_1 = 0.55 \pm 0.01$ V or $V_2 = 6.4 \pm 0.1$ V.

FIGURE 10 Three digital meters reading the voltage across the same resistor

Investigate, evaluate and communicate

6 **Assess** the statement 'You can't have a parallax error with a digital stopwatch.'

7 A voltmeter kept giving readings 0.5 V higher than expected. **Evaluate** this situation and state what sort of error this would be and how it could be fixed.

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Error analysis

» Increase your knowledge
Who is the best timer?

» Increase your knowledge
Error and uncertainty

0.5 Reporting the results of experimental measurements

KEY IDEAS

In this section, you will learn about:

+ single and repeated measurements of the same quantity
+ absolute and percentage uncertainty as a measure of precision
+ absolute and percentage error as a measure of accuracy.

Uncertainty in experimental measurements

There are two types of experimental measurements:

1 single measurements
2 repeated measurements of the same quantity.

When an experimental measurement is reported, it should be stated as the best estimate of the measurement followed by the uncertainty in the measurement(s).

Single measurement

A single measurement is a one-off measurement. A common example comes from an Ohm's law experiment that involves setting up a circuit containing a voltmeter and ammeter and taking pairs of readings (voltage and corresponding current) as the voltage is increased. Because it is a series of single readings, no average can be made. This would be reported as the best estimate of voltage ± scale reading uncertainty. For example, a non-digital scale reading single measurement from a voltmeter might be reported as 0.75 ± 0.05 V.

An old rule says: 'You should never rely on a single reading or result for any quantity'. In the example of the Ohm's law experiment, once the maximum voltage has been reached the measurements would need to be repeated. It is possible that the wire had heated up at high voltages and the subsequent measurements will not be the same.

There may be an occasion when only one measurement is possible. A 100 m race at school is timed with a stopwatch and the reading is 12.79 s. How should a physicist report this? The stopwatch is digital with the smallest increment of .01, so this would be reported as 12.79 ± 0.01 s. However, the random effects of reaction time are not included in this result. For stopwatch times, the greatest uncertainty is not in the device itself (±0.01 s) but in human error. Typical reaction time for high school students is about 0.20 s, so you would report the result as 12.79 ± 0.20 s.

FIGURE 1 For stopwatch times, the greatest uncertainty is not in the device itself but in human error.

If the diameter of a piece of wire was measured using a Vernier calliper just once at 0.62 mm, this would be reported as 0.62 ± 0.01 mm (0.01 being the smallest increment of the device).

Repeated single readings

Making repeated single measurements and averaging them is more typical of physics experiments at school and is an effective way of reducing the uncertainty in a measurement.

In reporting the measurements, three things need to be stated:

1 **Best estimate** from the set of measurements. This is usually the mean (average), x, of the measurements. The median (middle value) could also be reported, but this is less common.

2 **Absolute uncertainty** of the measurements about the mean (best estimate). This uncertainty is usually reported by half the range of the measurements (calculated by subtracting the highest from the lowest value and dividing by two). It can be thought of as the deviation of values around the mean and so has the symbol δ (the lowercase delta or Greek 'd').

   Absolute uncertainty of the mean: $\delta = \pm\frac{(x_{max} - x_{min})}{2}$

3 **Units**.

For example, the diameter of a piece of wire is measured four times using a Vernier calliper and the readings are 0.62, 0.63, 0.63 and 0.64 mm. The best estimate is the average (mean) of 0.63 mm and the range is 0.64 – 0.62 = 0.02 mm. Half the range of 0.02 mm is 0.01 mm, so you would report the results as 0.63 ± 0.01 mm.

Sometimes it is enough to know the range between the highest and the lowest values. However, for a small set of values (typical in senior physics) this may not give useful information about the spread of the readings between the highest and the lowest values. A large spread could arise because a single reading is very different from the others. As an alternative to absolute uncertainty of the mean, the **standard deviation** (SD, or sigma, σ) could also be reported. For example, the SD of the four results (0.62, 0.63, 0.63, 0.64 mm) is 0.008 mm. Therefore, the results could also be reported as 0.63 ± 0.008 mm (but this reduces to 0.63 ± 0.01 mm when expressed to two decimal places). Either method is okay.

standard deviation
a measure of the amount of variation of a set of data values. A low standard deviation means the data points tend to be close to the mean of the set, while a high standard deviation indicates that the data points are spread out over a wider range of values

WORKED EXAMPLE 0.5A

A 40.0 cm long pendulum is set oscillating and timed for 10 oscillations (in seconds) for a total of eight trials. The times were: 17.60, 17.59, 17.66, 17.63, 17.68, 17.63, 17.56, 17.53. Calculate the absolute uncertainty of the mean.

SOLUTION

Average (mean) $\bar{x} = \frac{\Sigma x_i}{n}$

$= \frac{140.88}{8}$

$= 17.61$ s

Absolute uncertainty of the mean:

$\delta = \pm\frac{(x_{max} - x_{min})}{2}$

$= \pm\frac{17.68 - 17.53}{2}$

$= \pm\frac{0.15}{2}$

$= \pm 0.075$ s (0.07 s)

You would report this as:

Time (for 10 oscillations) = 17.61 ± 0.07 s

Time (for 1 oscillation) = 1.761 ± 0.007 s

(Note that the uncertainty is also divided by 10.)

From Worked example 0.5A, you can see why it is good to measure the total time of such sequential events as the uncertainty is divided by the number of events. If you measured just one oscillation, you would have to record your reaction time (0.10 s) as the uncertainty, and thus report the result as 1.76 ± 0.10 s.

When using standard deviation, the SD (σ) is 0.050 s for the average of 10 swings for the eight trials, or 0.005 s for the one swing. This would be reported as 1.76 ± 0.005 s (or 1.76 ± 0.01 s to two decimal places).

Propagation of uncertainties

When data is collected, something needs to be done with it. For example, if you gather mass, time or voltage data, this will be used in a formula to calculate other quantities (such as speed, acceleration, density or resistance). You may want to compare the data with accepted values of acceleration due to gravity, density and specific heat.

If you add, subtract, multiply or divide the data, you will need to do something with the uncertainty associated with each measurement. Firstly, you may need to get the data into the right form. This may involve converting absolute uncertainty to percentage uncertainty.

Absolute and percentage uncertainties

percentage uncertainty an indicator of uncertainty in which the range of values for a measurement result (the uncertainty) is expressed as a percentage of the average measurement or best estimate

The uncertainties we have been talking about are called 'absolute' uncertainties. We can express this as a **percentage uncertainty** ($\delta\%$) by dividing by the observed value and multiplying the result by 100 to give a percentage.

Percentage uncertainty:

$$\delta\% = \frac{\text{absolute uncertainty } (\delta x)}{\text{observed measurement } (x_o)} \times 100\%$$

$$= \frac{\delta x}{x_O} \times 100\%$$

WORKED EXAMPLE 0.5B

Calculate the percentage uncertainty for the following:

a A digital multimeter reads 0.818 V and has an absolute uncertainty of ±0.001 V. This is written as 0.818 ± 0.001 V.

b A voltmeter reading of 0.75 ± 0.05 V.

SOLUTION

a $\delta\% = \frac{\text{absolute uncertainty } (\delta)}{\text{observed measurement } (X_O)} \times 100\%$

$= \frac{\delta X}{X_O} \times 100\%$

$= \frac{0.001}{0.818} \times 100\%$

$= 0.12\%$

This would be written as 0.818 V ± 0.12%.

b $\delta\% = \frac{\text{absolute uncertainty } (\delta X)}{\text{observed measurement } (X_O)} \times 100\%$

$= \frac{\delta X}{X_O} \times 100\%$

$= \frac{0.05}{0.75} \times 100\%$

$= 6.7\%$

This would be written as 0.75 V ± 6.7%.

Caution with temperature percentage errors

When calculating percentage errors for temperature, you need to convert Celsius temperatures (°C) to kelvin temperatures (K) by adding 273 before performing any uncertainty calculation. The formula to convert Celsius to kelvin is: K = °C + 273

What would be the percentage uncertainty in the temperature of an ice cube at 0.0°C? If the absolute uncertainty was ±0.5°C, the percentage uncertainty would be

$\frac{0.1}{0.0} \times 100\% =$ infinity. This is clearly wrong and doesn't make sense. For this reason, we convert Celsius to kelvin.

However, in temperature measurements scientists are usually interested in a **change** in temperature ($\Delta T = T_{final} - T_{initial}$), so sometimes we can work with Celsius temperatures.

TABLE 1 Estimating uncertainty with temperature

Measurement	Celsius	Kelvin
Best estimate and absolute uncertainty	23.0 ± 0.1°C	300.0 ± 0.1 K
Temperature	23.0°C	300.0 K
Absolute uncertainty	±0.1°C	±0.1 K
Percentage uncertainty	$\frac{0.1}{22.0} \times 100\% = 0.4\%$ Wrong	$\frac{0.1}{300.0} \times 100\% = 0.03\%$ Correct

Uncertainty calculations

To add, subtract, multiply or divide measurements, the absolute and percentage uncertainties may be required.

When performing uncertainty calculations, the following rules apply:

- For addition and subtraction, add **absolute** uncertainties.
- For multiplication and division, add **percentage** uncertainties.

WORKED EXAMPLE 0.5C

The winning time for the 100 m sprint in the 2016 Rio Olympic Games was 9.81 s. Assuming the time was 9.81 ± 0.01 s and the distance was 100.0 ± 0.1 m, calculate the average speed.

SOLUTION

Speed = $\frac{\text{distance}}{\text{time}}$, so we need to work with percentage uncertainties.

Distance = 100.0 ± 0.1 m

$= 100.0 \pm \left(\frac{0.1}{100.0} \times 100\right)\%$

= 100.0 ± 0.1% (converted to % uncertainty)

Time = 9.81 ± 0.1 s

$= 9.81 \pm \left(\frac{0.1}{9.81} \times 100\right)\%$

= 9.81 ± 0.10% (converted to % uncertainty)

Average speed = $\frac{100.0}{9.81} \pm (0.1 + 1.10)\%$ (add percentage uncertainties)

= 10.194 m s^{-1} ± 0.20% (result)

$= 10.194 \pm \frac{0.20}{100} \times 10.194$ (convert back to absolute uncertainty)

= 10.194 ± 0.020 m s^{-1}

= 10.2 ± 0.02 m s^{-1} (correct significant figures)

WORKED EXAMPLE 0.5D

A golf ball has a mass as measured on a digital scale of 46.93 ± 0.01 g. The golf ball is raised to a vertical height of 755.0 mm as measured on a metre ruler that is calibrated in 1 mm divisions, so a reading has an uncertainty of ±0.5 mm. Calculate the gravitational potential energy (E_p) of the ball (use $g = 9.807$ m s^{-2}).

SOLUTION

Mass of ball (m) = 46.93 ± 0.01 g

$$= 46.93\text{ g} \pm \left(\frac{0.01}{46.93} \times 100\right)\%$$

$$= 46.93\text{ g} \pm 0.021\%\ (0.04693\text{ kg} \pm 0.021\%)$$

Height of ball (h) = 755.0 ± 0.5 mm

$$= 755.0\text{ mm} \pm \left(\frac{0.5}{755.0} \times 100\right)\%$$

$$= 755.0\text{ mm} \pm 0.066\%\ (0.7550\text{ m} \pm 0.066\%)$$

$E_p = mgh$

$= 0.04693 \times 9.807 \times 0.7550 \pm (0.021\% + 0.066\%)$

$= 0.34748309505\text{ J} \pm 0.087\%$

$= 0.3475\text{ J} \pm 0.087\%$ (to 4 significant figures)

E_p absolute uncertainty $= \frac{0.087}{100} \times 0.3475$

$= 0.0003\text{ J}$

$E_p = 0.3475 \pm 0.0003\text{ J}$

Study tip

Some more worked examples demonstrating uncertainty calculations can be found on your obook assess.

Accuracy of experimental measurements

Accuracy and precision are terms often used when evaluating experimental results. It is important they are used correctly. We have seen that uncertainty is used to express the precision of a set of measurements. However, students often find their results are different from the accepted result, even though they performed the experiment as carefully as possible and read the instruments as best they could. This measurement discrepancy is also known by the term 'error' and is a measurement of the accuracy of a result.

Accuracy is how close the experimental result (measurement) is to the accepted result. Absolute error is the difference between the accepted result and the observed result.

Absolute error = observe result – accepted result

$$E_a = |x_O - x_A|$$

The straight lines (|) in the equation indicate the 'absolute value', which means the sign (+/–) of the answer is ignored. The lines are called modulus signs.

Percentage error is the absolute error expressed as a percentage of the accepted value.

$$\text{Percentage error } (E\%) = \frac{\text{measured value} - \text{true value}}{\text{true value}} \times 100\%$$

$$E\% = \frac{E_a}{A} \times 100\%$$

WORKED EXAMPLE 0.5E

A student measured the acceleration due to gravity as 9.73 m s^{-2} whereas the accepted value at their location is 9.813 m s^{-2}. Calculate the:

a absolute error

b percentage error.

SOLUTION

a $E_a = |x_O - x_A|$

$= |9.73 - 9.813|$

$= 0.08\text{ m s}^{-2}$ (to the correct number of significant figures) b $E\% = \frac{E_a}{A} \times 100\%$

$= \frac{0.08}{9.813} \times 100\%$

$= 0.8\%$

CHECK YOUR LEARNING 0.5

Describe and explain

1 **Summarise** the meaning of the following: absolute uncertainty, percentage uncertainty, precision, accuracy, absolute error, percentage error.

2 A student carries out an investigation to measure the time taken for 10 complete swings of a pendulum. The following values are obtained: 3.1 s, 3.8 s, 3.3 s, 4.1 s and 3.4 s. **Calculate** the absolute and percentage uncertainty.

3 A student obtained a value of 9.74 m s^{-2} for the acceleration due to gravity. **Calculate**:

- a the absolute error
- b the percentage error.

Apply, analyse and interpret

4 The period for a simple pendulum of length 80 cm was measured in triplicate and found to be 1.79 s, 1.85 s and 1.72 s. **Determine** the:

- a mean value for the period
- b absolute uncertainty
- c percentage uncertainty.

5 A digital ammeter shows the current in a circuit to be 0.10 A. **Determine** whether the percentage uncertainty in the value of I^2 will be:

- a 1%
- b 2%
- c 5%
- d 20%.

6 A carbon resistor of nominal resistance 330 ohms is manufactured to a tolerance of 5%. This is, in effect, the maximum percentage error. **Determine** what the range of resistance this resistor could have.

Investigate, evaluate and communicate

7 Use your ruler to measure your student book. Use your measurement to **determine** the following (include the uncertainty of each result):

- a the surface area of the front cover
- b the total external surface area
- c the volume
- d the thickness of one page.

8 Students were measuring the acceleration due to gravity by dropping a ball from a measured height and timing how long it took to fall. Their results are shown in Table 2.

TABLE 2

Group	Height h (m)	Trial 1 (s)	Trial 2 (s)	Trial 3 (s)
A	0.50	0.37	0.44	0.50
B	2.00	0.75	0.87	0.94

To **calculate** the acceleration, the students used the following formula:

$a = \frac{2 \times s}{t^2}$

where s = drop height, and t = average time. The accepted value is 9.81 m s^{-2}.

For each group, **determine** the percentage uncertainty of the mean and their percentage error.

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  Recording and analysing data
- » Video worksheet
  Recording and analysing data
- » Increase your knowledge
  Worked examples demonstrating uncertainty

0.6 Graphical analysis

KEY IDEAS

In this section, you will learn about:

+ graphical representations of data
+ processing of data
+ trends, patterns and relationships.

Graphs are a useful way of showing how one quantity depends on another. On a graph, the horizontal axis is where the independent variable (or the cause) is plotted. This also includes variables that progress regardless of the experiment. An example is time elapsed, for time continues on regardless of whether any experiment is being carried out. The effect of that cause is plotted on the vertical axis – this is called the dependent variable.

Data is obtained by measurement of a physical attribute or attributes (such as length, time or colour). Data may be quantitative (numerical information, such as length and time) or qualitative (information that is non-numerical, such as colour).

Primary data is data collected directly by a person or group. Secondary data is data collected by a person or group other than the person or group using the data.

Extending and reading a graph beyond the last plotted point is called extrapolation. Inferring a reading between plotted points is called interpolation.

FIGURE 1 Primary data is collected directly by a person or group.

Linear relationships

Linear and directly proportional

A linear relationship is a straight line when graphed. A directly proportional relationship is also linear, but it is a special case that goes through the origin (0,0).

Consider an experiment to determine how much a certain rubber band stretches when masses are hung vertically from it. Table 1 shows the data recorded from the experiment.

The relationship becomes obvious when the points are plotted (Figure 2). Note that each point is plotted as a dot that is big enough to still be seen once a line of best fit is drawn. The

TABLE 1 Directly proportional data

Independent variable: mass (g)	0	20	40	60	80
Dependent variable: stretch (mm)	0	10	21	28	42

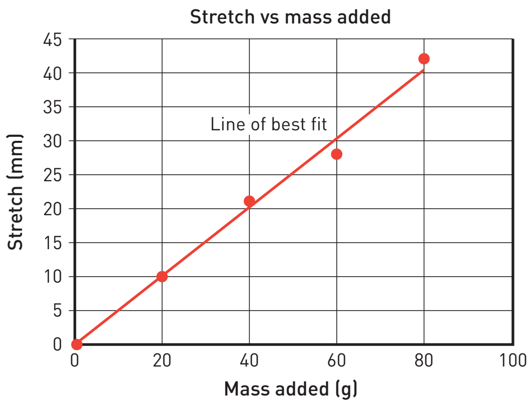

FIGURE 2 Graph of directly proportional data

line of best fit has as many points on the line as possible. There are usually some points that don't sit exactly on the line, so the line should be drawn with the same number of points below it as above it.

Scientists and engineers use a complex mathematical procedure (the method of least squares) to determine where the line of best fit should be. Any point that is a long way out of place is called an **outlier** or an **anomaly** and is said to be false. An outlier is a value that 'lies outside' (is much smaller or larger than) most of the other values in a set of data. It is a legitimate data point originated from a real observation. An anomaly is something that deviates from what is standard, normal or expected. It is illegitimate and produced by an artificial process (such as mistakes, wrong equipment or a fake result).

outlier
a value that is much smaller or larger than most of the other values in a set of data

anomaly
a false data point often the result of a faulty observation or wrong equipment

Any individual outlier or anomaly should be noted and the reasons for its existence can be discussed – but it should be left off the line of best fit. Most people consider anomalies and outliers to be the same thing, but it is important to be aware of the differences between them.

If the line of best fit is straight and goes through the origin (as in Figure 2), it takes the general form of $y \propto x$. The proportional sign ($\propto$) can be replaced by an equals sign and a constant (m).

Equation of a straight line:

$$y = mx$$

or

$$y = mx + c$$

where x and y are the variables, m is the **gradient** or slope of the line and c is the y-intercept or point where the line cuts the y-axis.

gradient
the slope of a graph

In the graph of mass versus stretch (Figure 2), the intercept c is zero. The slope is found by dividing the change in y value by the change in the x value for the same section of the line. This can be written as:

$$\text{Slope } (m) = \frac{\text{change in } y}{\text{change in } x} = \frac{\Delta y}{\Delta x} = \frac{y_2 - y_1}{x_2 - x_1}$$

Students often find it easier to remember this as 'rise over run', where 'rise' refers to the y-axis and 'run' refers to the x-axis.

The slope of the graph in Figure 2 is given by: $m = \frac{40 - 0}{80 - 0} = 0.5$ and the intercept c is zero. Thus, for every 1 g change in mass (x-axis), the rubber band changes by 0.5 mm in length (y-axis). Be careful with significant figures!

Note that you can't just take the first and last values away from each other to get the rise or the run as the last plotted point is not on the line. You need to use the x and y coordinates of the line and not just the points.

Linear but not directly proportional

The graph of the rubber band stretching (Figure 2) is both linear and directly proportional. The graph in Worked example 0.6 is linear but not directly proportional as it doesn't go through (0, 0).

WORKED EXAMPLE 0.6

The position of a car on a road was noted every 5 seconds and the data in Table 2 was obtained:

TABLE 2 Linear data that is not directly proportional

Time (s)	0	5	10	15	20
Distance (m)	16	23	34	41	50

a Plot the data.

b Calculate the average velocity (slope).

c State the intercept.

d State the equation for the line.

e Predict the position at 25.0 s.

f State the position at 12.5 s.

g Explain whether the graph is directly proportional.

SOLUTION

a Time is the independent variable and is plotted on the horizontal axis (*x*-axis). Distance is the dependent variable and is plotted on the vertical axis (*y*-axis). A line of best fit can be drawn.

b Slope $= \frac{50.0 - 16.0}{20.0 - 0.0} = 1.7\ \text{m s}^{-1}$

c Intercept = 16.0 m

d The equation for a straight line is $y = mx + c$. This can be expressed using the values calculated from the data, hence $s = 1.7t + 16$.

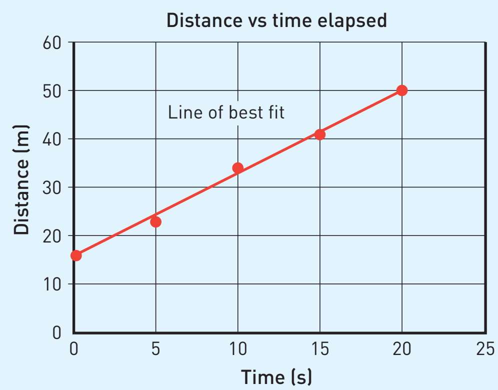

FIGURE 3 Graph of data shows a linear but not directly proportional relationship

e The graph must be extended to determine the position at 25.0 s. This is called extrapolation. The value at 25.0 s is approximately 58 m. Alternatively, the value $t = 25$ s could be substituted into the equation $s = 1.7t + 16$ to give the answer of 58.5 m.

f A value between two measured points is determined by interpolation. At 12.5 s the value is 37 m.

g The graph is not directly proportional as it doesn't go through (0, 0). However, it is linear as it is a straight line.

Non-linear relationships

A non-linear relationship is not a straight line when graphed. The most common non-linear relationships you will meet in physics are power, exponential and logarithmic relationships, as outlined in Table 3.

TABLE 3 Examples of common non-linear relationships

Type of relationship	Equation	
Power	$y \propto x^a$	parabolic ($a = 2$): $y \propto x^2$ inverse ($a = -1$): $y \propto x^{-1}$ or $y \propto \frac{1}{x}$ inverse-square ($a = -2$): $y \propto x^{-2}$ or $y \propto \frac{1}{x^2}$ square root $\left(a = \frac{1}{2}\right)$: $y \propto x^{\frac{1}{2}}$ or $y \propto \sqrt{x}$
Exponential	$y \propto e^{kt}$	natural exponential: $y \propto e^{kt}$
Logarithmic	$y \propto 10^x$	

Power relationships

Parabolic relationship

Parabolic relationship: $y \propto x^2$, where the power a is 2.

The most common relationship you will encounter is the parabolic relationship. An example is the relationship between the distance a rock has fallen from the top of a cliff and the time elapsed. The data in Table 4 shows these variables and Figure 4 shows a graph of the distance against the time.

Other phenomena that exhibit parabolic relationships are the paths of comets (except Halley's comet, which is elliptical), curved mirrors in telescopes and projectiles (arrows in flight).

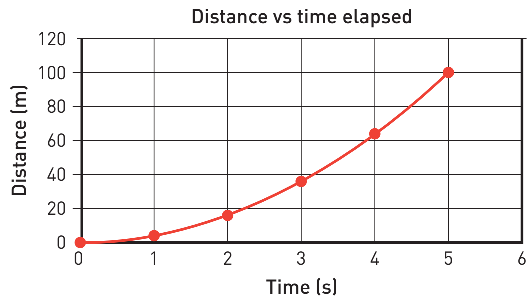

FIGURE 4 Parabolic graph (a parabola)

TABLE 4 Parabolic data

Time (s)	0	1	2	3	4	5
Distance (m)	0	4	16	36	64	100

Inverse relationship

Inverse relationship: $y \propto x^{-1}$ or $y \propto \frac{1}{x}$, where the power a is –1.

Consider a case in which the volume of gas in a syringe is measured as the pressure on the syringe is increased by adding weights to the platform. The graph in Figure 5 shows an inverse relationship (also called an inversely proportional relationship).

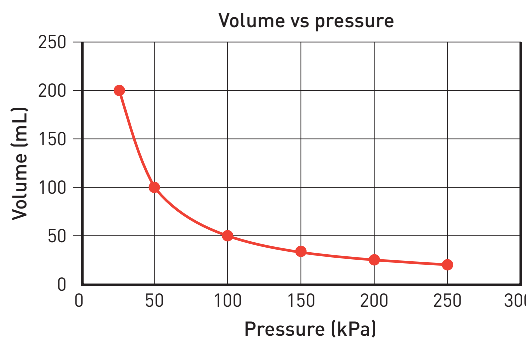

FIGURE 5 Inverse graph

Inverse-square relationship

Inverse-square relationship: $y \propto \frac{1}{x^2}$, where the power a is –2.

An inverse-square relationship looks similar to an inverse relationship but has a much sharper bend. This type of relationship is very common in physics. For example, the variation in gravitational force with distance is given by $F \propto \frac{1}{d^2}$, as shown in Figure 6.

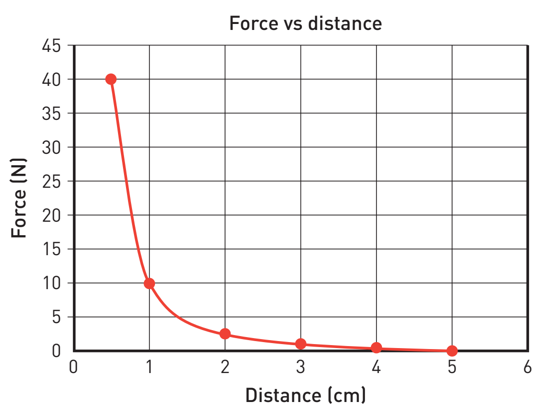

FIGURE 6 Inverse-square graph

Square root relationship

Square root relationship: $y \propto x^{\frac{1}{2}}$, where $a = \frac{1}{2}$.

Also written as $y \propto \sqrt{x}$ or $y \propto \sqrt[2]{x}$.

An example of a square root relationship involves letting a ball roll down a ramp. The speed at the bottom of the ramp varies with the square root of the height of the ramp ($v \propto \sqrt{h}$), as shown in Figure 7.

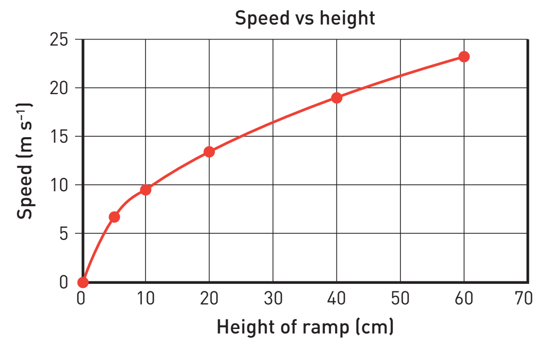

FIGURE 7 Square root graph

Study tip

A summary of some common graph shapes can be found on your obook assess.

Exponential relationships

Exponential relationship: $y = a^x$

The natural exponential function is $y \propto e^{kt}$ or $y = y_o e^{kt}$.

Physics has some quantities that are related exponentially. For example, in a radioactive substance, the number of radioactive atoms remaining follows natural exponential decay (as long as the remaining number of atoms is large). The breakdown (decay) of a radioactive substance is given by activity $\propto e^{-kt}$, where the a value is e, the 'natural' base (2.718). The symbol k is a constant (-k for decay, +k for growth), and t = time elapsed. This is shown in Figure 8.

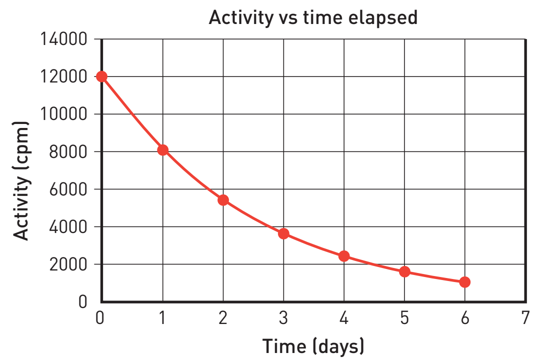

FIGURE 8 Natural exponential decay

Logarithmic relationships

Logarithmic relationship: $y = log_a x$

In a quiet room, people can hear a pin drop onto a bench. The amount of energy released is very small, and human hearing is very sensitive when things are quiet. The human ear also has to be able to hear things such as an explosion, which could be a trillion (10^{12}) times louder. The sensitivity of human hearing is good for low power sounds but reduced at high power. This is an example of a logarithmic relationship: $D = 10\log_{10}\left(\frac{I}{I_o}\right)$, as shown in Figure 9.

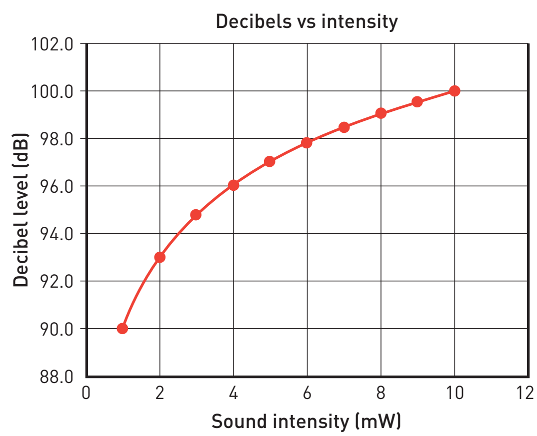

FIGURE 9 Logarithmic graph

CHECK YOUR LEARNING 0.6

Describe and explain

1 **Explain** if it is usual to plot the independent variable on the vertical or the horizontal axis.

2 **Define** the following: dependent variable, independent variable, analyse, anomaly, outlier, relationship, reliable, reliability, trend, line of best fit.

3 **Sketch** a graph of each of the sets of data given below. In each case, draw the lines of best fit. (Note*:* the independent variable is listed first.)

a **TABLE 5**

Diameter of circle (cm)	0.0	4.0	8.0	12.0
Circumference of circle (cm)	0.0	12.5	25.4	37.3

b **TABLE 6**

Time (years)	0.0	1.0	2.0	3.0	4.0
Height of tree (m)	0.0	0.32	0.66	1.00	1.30

Apply, analyse and interpret

4 For the graphs shown in Figure 10, **determine** the graph that best represents the following relationships:

a *y* is proportional to *x*

b *y* is inversely proportional to *x*

c *y* is independent of *x*

d *y* is proportional to x^2.

5 a If $W = kV$, **determine** the effect on *W* of:

i tripling *V*

ii halving *V*.

b **Explain** what a graph of *W* as a function of *V* looks like.

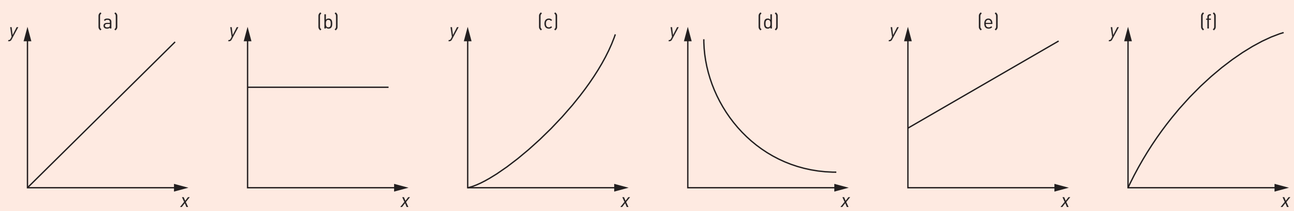

FIGURE 10 Graphs with different relationships

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Plotting a graph

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Common graph shapes

0.7 Linearising graphs and evaluating errors

KEY IDEAS

In this section, you will learn about:

- linearising graphs
- looking for systematic errors.

Even though a graph may look like it has a particular shape, its relationship cannot be known for sure. For example, $y \propto \frac{1}{x}$ and $y \propto \frac{1}{x^2}$ are very similar and are hard to tell apart. The relationship could also be in-between them, such as $y \propto \frac{1}{x^{1.5}}$. The only way to tell is to plot them in the form of $y = mx$. If that graph is linear, then you have confirmed the suspected relationship. This is called **linearising** a graph.

linearising transforming non-linear data by applying a mathematical function to one of the variables so that the relationship between the variables becomes closer to a straight line

The relationship $y \propto \frac{1}{x}$

If you already have a straight-line relationship such as $y \propto x$, then a graph of y versus x is a straight line. However, if you have $y \propto \frac{1}{x}$, then a graph of y versus x is non-linear. Let's look at this using the data in Table 1 and plotting y versus x. The graph of V versus P is non-linear (Figure 1) and instead looks like a $y \propto \frac{1}{x}$ graph.

TABLE 1 Original data set showing a suspected inverse relationship

Pressure *P* (kPa)	*x*	1	2	3	4	5
Volume *V* (mL)	*y*	3.0	1.5	1.0	0.8	0.6

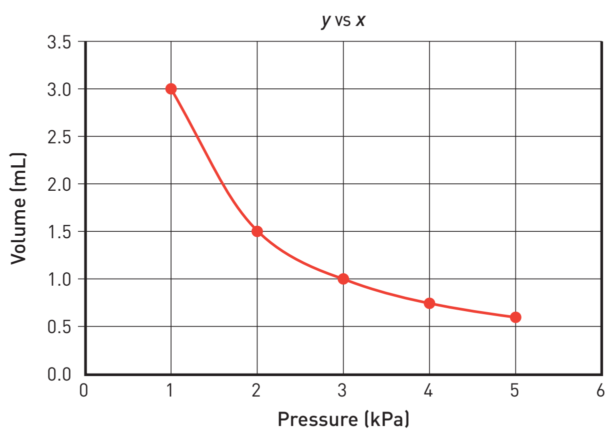


FIGURE 1 A *P* versus *V* graph of the data is not linear – it appears inverse.

You can try to linearise the graph by calculating $\frac{1}{x}$ (Table 2) and plotting y versus $\frac{1}{x}$ (Figure 2). If it is a straight line, then you have confirmed the relationship $y \propto \frac{1}{x}$ (which is $V \propto \frac{1}{P}$ in this case).

If the $y \propto \frac{1}{x}$ graph is still curved, then it may be a $y \propto \frac{1}{x^2}$ relationship.

TABLE 2 Original data and an inverse transformation of *P*

Pressure *P* (kPa)	x	1	2	3	4	5
$\frac{1}{\text{Pressure}}$ **(kPa⁻¹)**	$\frac{1}{x}$	1.00	0.50	0.33	0.25	0.20
Volume *V* (mL)	y	3.0	1.5	1.0	0.8	0.6

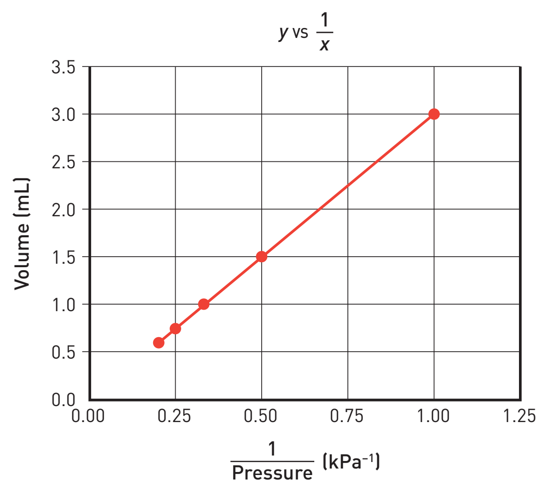


FIGURE 2 A *V* versus $\frac{1}{P}$ graph of the data gives a straight line, so it is a $y \propto \frac{1}{x}$ relationship.

The relationship $y \propto \frac{1}{x^2}$

Consider the force between two magnets at various distances (Table 3).

TABLE 3 Original data and the inverse-square transformation of *d*

Distance *d* (mm)	x	0.5	1.0	2.0	3.0	4.0	5.0
Force (N)	y	12.0	3.0	0.8	0.3	0.2	0.1
$\frac{1}{d^2}$	$\frac{1}{x^2}$	4.00	1.00	0.25	0.11	0.06	0.04

A graph of y versus x is non-linear and looks more like a $y \propto \frac{1}{x^2}$ graph (Figure 3).

A graph of y versus $\frac{1}{x^2}$ is a straight line (Figure 4), so this confirms it is a $y \propto \frac{1}{x^2}$ relationship.

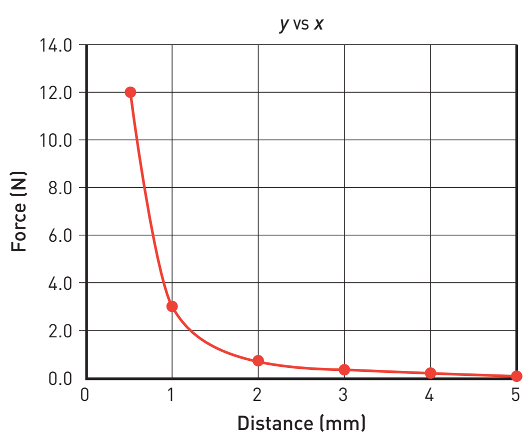


FIGURE 3 A *y* versus *x* graph of the data does not give a straight line.

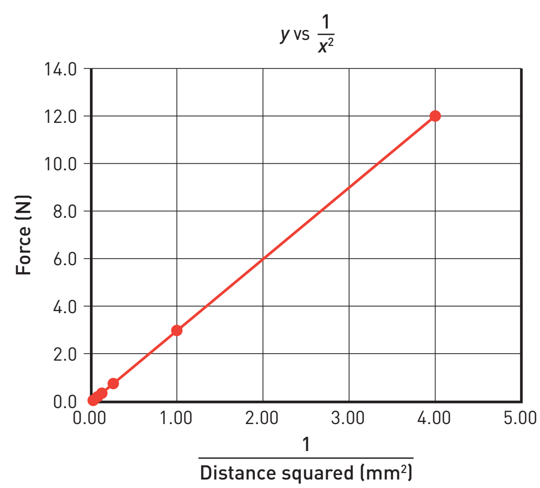


FIGURE 4 The straight line indicates it is a $y \propto \frac{1}{x^2}$ relationship.

The relationship $y \propto x^2$

Consider the data of a car accelerating from the traffic lights (Table 4).

TABLE 4 Original data – suspected square relationship

Time (s)	x	0	1	2	3	4	5
Speed (m s^{-1})	y	0	2	8	18	32	50

The graph of y versus x is shown in Figure 5. It looks very much like a $y \propto x^2$ relationship. To confirm this, we would linearise the graph by calculating x^2 and plotting y versus x^2.

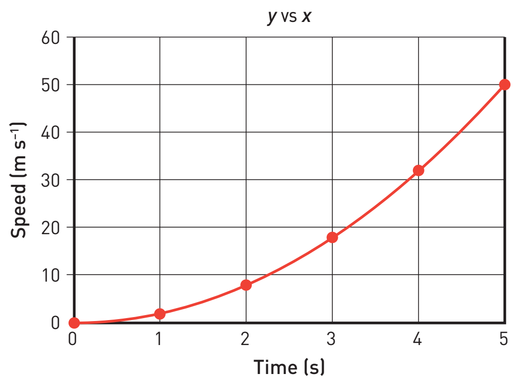


FIGURE 5 This non-linear graph is a suspected square relationship.

Using graphs to evaluate errors

Earlier we defined **systematic error** as the contribution to the uncertainty in a measurement result that is identifiable and quantifiable. Examples of systematic errors include zero error, parallax error and calibration error. You may be asked to identify systematic errors in first- or second-hand data. You can do this in two main ways with linearised data:

1 when the line of best fit doesn't go through the origin (Figure 6(a))

2 when the line is not straight (Figure 6(b)).

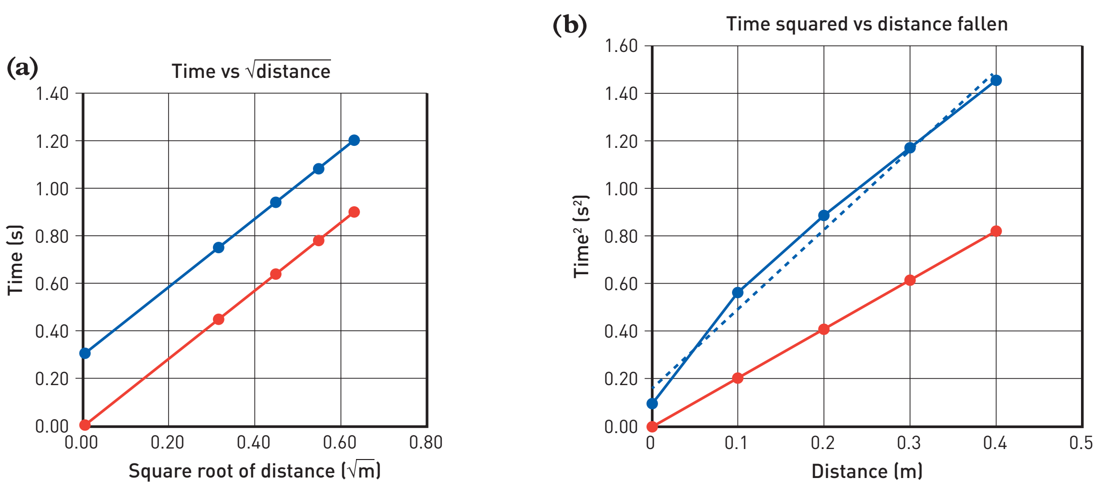


FIGURE 6 (a) For a $y \propto \sqrt{x}$ relationship, plotting y vs $\sqrt{x}$ gives a straight line (red). However, when there are systematic errors in y, the graph doesn't go through the origin (blue). (b) For the same relationship, plotting y^2 vs x still gives a straight line (red), but when there are systematic errors in y, the graph looks curved (blue).

'Goodness of fit'

When you linearise data, it is usual to calculate the 'goodness of fit' index known as R^2 (R-squared) value. Excel (and other graphing software) can perform this calculation easily. It is a useful index of how well a line of best fit (trend line) fits the linear data points. The higher the R^2 value, the better the trend line fits your data. For example, look at Tables 5 and 6 showing two separate sets of data collected by students plotting voltage and current data for an Ohm's law experiment. Figure 7 shows the graph of each data set.

TABLE 5 Group 1's data

Current (A)	0.0	10.0	20.0	30.0	40.0	50.0	60.0
Voltage (mV)	0	1.4	2.2	3.6	5.1	5.81	7.2

TABLE 6 Group 2's data

Current (A)	0.0	10.0	20.0	30.0	40.0	50.0	60.0
Voltage (mV)	0	1.8	1.8	3.6	5.6	5.5	7.2

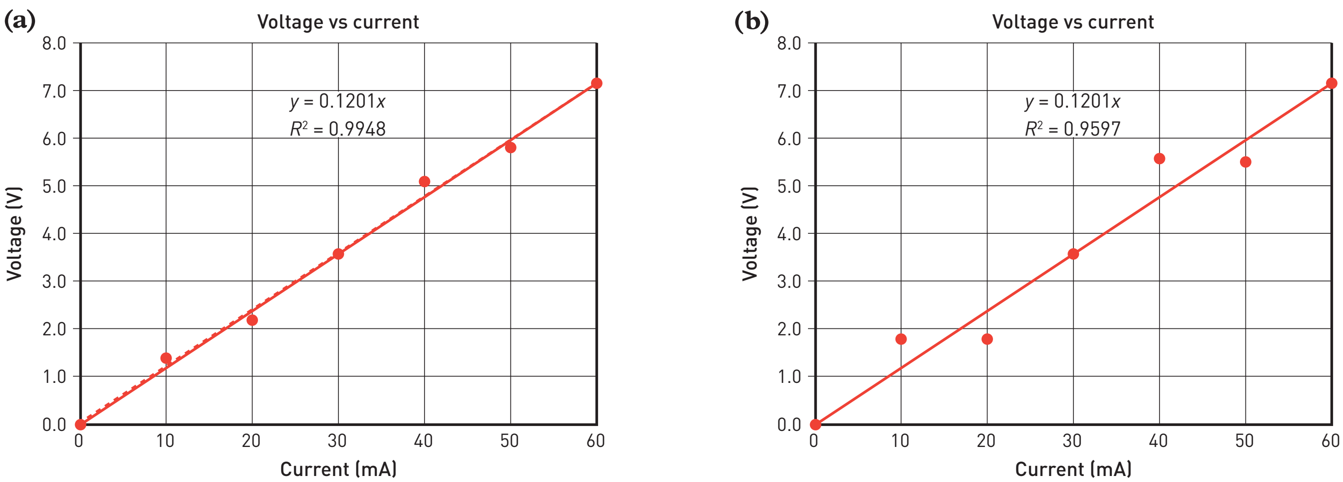


FIGURE 7 Voltage versus current graphs for (a) Group 1 and (b) Group 2

Figure 7 shows that Group 1 had a lower scatter of results, so their R^2 value was high at 0.9948. Group 2's data was more scattered, so their R^2 value was low at 0.9597. We can also say Group 1's measurements were more precise (less scattered) than Group 2's. Note that the gradient is the same at 0.120. The R^2 value is about the precision (scattering) of your data. It doesn't say anything about the accuracy (closeness to the real value).

Error bars and uncertainty

The measurement uncertainty associated with a particular mean value can be easily displayed on a graph using error bars. These are vertical or horizontal lines that are added to each data point that represent the absolute uncertainty at that point. For example, imagine an experiment in which a ball is dropped from a height of 5.0 m, and the displacement recorded every 0.20 s.

The graph in Figure 9a (on the next page) shows vertical error bars for the measurement of displacement (vertical axis). For most experiments, the uncertainty in the independent

FIGURE 8 Excel can calculate the 'goodness of fit' index easily.

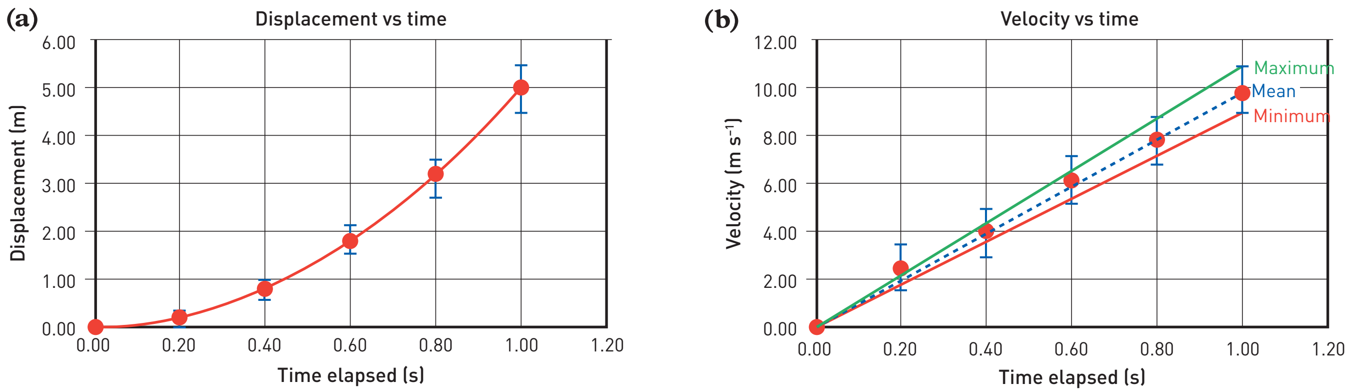


FIGURE 9 (a) Vertical error bars show the zone of uncertainty for the displacement values. (b) A graph of the calculated velocity with added vertical error bars.

variable (horizontal axis) will be very low and can be neglected. The line of best fit should be midway between the caps of the error bar.

The graph in Figure 9b shows a graph of the velocity at each time, which was calculated using the formula: $v = 2 \times v_{av} = \frac{2s}{t}$.

A line of best fit (blue) has been drawn and we can calculate its gradient as 9.90 ms^{-2}.

Two other trendlines have been added with either maximum or minimum gradient:

maximum line of best fit
a line of best fit of maximum gradient within the bounds of the error bars

minimum line of best fit
a line of best fit of minimum gradient within the bounds of the error bars

- a **maximum line of best fit** (green) that fits within the bounds of the error bars. Its gradient is $\frac{10.90 - 0}{1.00 - 0} = 10.9 \text{ m s}^{-2}$.
- a **minimum line of best fit** (red) that fits within the bounds of the error bars. It has a gradient of $\frac{8.90 - 0}{1.00 - 0} = 8.90 \text{ m s}^{-2}$.

The uncertainty associated with the gradient can now be calculated:

$$\delta = \pm\frac{(x_{\text{max}} - x_{\text{min}})}{2}$$

$$= \pm\frac{(10.90 - 8.90)}{2}$$

$$= \pm 1.00 \text{ m s}^{-1}$$

Expressed as percentage uncertainty:

$$\delta\% = \frac{\delta}{x_0} \times 100\%$$

$$= \frac{1.00}{9.9} \times 100\%$$

$$= 10.1\%$$

Thus, the gradient can be stated using absolute uncertainty as $m = 9.9 \pm 1.0$ m s^{-2}. If using percentage uncertainty, $m = 9.9$ m s^{-2} ± 10.1%.

The gradient in this case is the experimental value for acceleration due to gravity of 9.9 m s^{-1} with a minimum of 8.9 m s^{-2} and a maximum of 10.9 m s^{-2}. We could say that the experiment was accurate as the accepted value of 9.8 m s^{-1} is within our experimental range. However, as the range is large we could also say that there is a lot of uncertainty in the measurements (a lack of precision) that detracts from the result.

CHECK YOUR LEARNING 0.7

Describe and explain

1 **Explain** what it means to 'linearise' a relationship.

2 Students obtained a relationship $y \propto x$. **Explain** whether there is any need to linearise it.

Apply, analyse and interpret

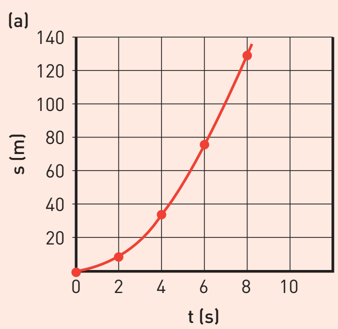
3 A plot of the variables *F* (vertical axis) and *v* (horizontal axis) gave a curve in the shape of $y \propto x^2$. **Determine** what you would need to plot to linearise it.

4 The displacement (*s*) in metres of a car at various times *t* (in seconds) is shown in Table 7.

TABLE 7

t (s)	0	2	4	6	8
s (m)	0	8	32	72	128

Graphs were drawn to show *s* vs *t* (Figure 10a) and *s* vs t^2 (Figure 10b).



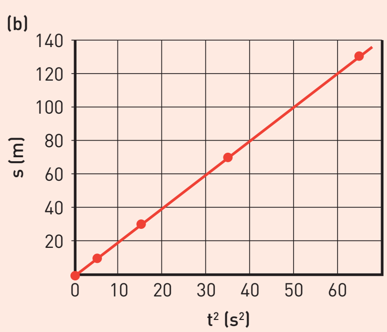


FIGURE 10 Graphs of (a) *s* vs *t* and (b) *s* vs t^2

Consider the relationship between *s* and *t*.

Investigate, evaluate and communicate

5 Table 8 gives data from an experiment where *F* and *r* are two related variables.

TABLE 8

F	72	48	24	18
r	2	3	6	8

The data was plotted to give the graph shown in Figure 11.

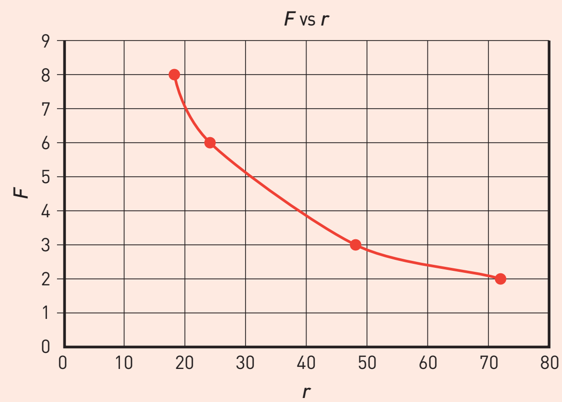


FIGURE 11 Graph of *F* vs *r*

a **Predict** the mathematical relationship suggested by this graph.

b **Sketch** another graph to confirm your prediction.

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» Video
Linearising a graph, adding a trendline and custom bars

» Video worksheet
Linearising a graph, adding a trendline and custom bars

» Weblink
Errors is science

0.8 The scientific method

KEY IDEAS

In this section, you will learn about:

+ steps in the scientific method.

FIGURE 1 The eight steps of the scientific method

The scientific method is a process of problem-solving used across all the sciences. It helps scientists investigate and explore ideas universally. The scientific method has eight steps, regardless of the science it is being applied to.

Steps in the scientific method

1. Identify the area of research
2. Collect information
3. Identify the research question and formulate a hypothesis
4. Design a research method to test the hypothesis
5. Collect and analyse the data
6. Draw a conclusion
7. Report findings
8. Test the conclusion

hypothesis
a considered opinion, theory or statement, based on research and evidence, about something that is yet to be tested

independent variable (IV)
a variable (often denoted by x) whose variation does not depend on that of another

dependent variable (DV)
the variable (often denoted by y) that responds to the independent variable. It 'depends' on the independent variable

Developing hypotheses

A **hypothesis** proposes cause-and-effect relationships, providing a tentative explanation for an observed phenomenon. The hypothesis needs to be expressed as a precise and unambiguous statement that can be supported or refuted by experiment. The hypothesis proposes the nature of the relationship between variables.

Variables

The **independent variable (IV)** is the element that is manipulated by the experimenter. The **dependent variable (DV)** is the element that is influenced by the independent variable, and subsequently measured.

Hypotheses typically take the form, 'as the independent variable is (increased or decreased), the dependent variable will (increase or decrease)'. For example, if a research question asks, 'How does the resistance of nichrome wire change with temperature?', the hypothesis could be, 'As the temperature of nichrome wire is increased, the resistance will decrease'. In this example, the independent variable is temperature and the dependent variable is resistance.

The method

The method needs to state the steps in the experiment and explain how the variables will be tested to support or refute the hypothesis. When writing a report, the method should be presented so that someone can replicate the experiment exactly as it was conducted.

The method should explain in detail how the variables were changed, as well as including exact information about measurements taken and how they were taken.

Types of data

Data can be nominal (labels), ordinal (in order), qualitative or quantitative. Physics typically deals with quantitative data. **Quantitative data** is numerical information about the variables. Quantitative data can be analysed using graphical information. **Qualitative data** is data that focuses on the descriptions of the characteristics of what is being studied.

Data tables and graphs are used to present the data scientifically. A data table should state what has been measured and show the raw data. The data should be displayed in forms that are appropriate to the data. Any calculations that need to be performed should also be represented.

qualitative data
relating to the non-numerical characteristics of a substance, an object or a phenomenon

quantitative data
relating to numerical data about a substance, an object or a phenomenon

Validity and reliability

What makes research and results valid or reliable? For an experiment to be reliable, it must be repeated several times to ensure that the results are due to the manipulation of the variables and not caused by chance. You may need to repeat the experiment using trials to ensure reliability, too.

For an experiment to be considered valid, the data must be directly related to the hypothesis. This does not mean that the data needs to support the hypothesis – it can also refute the hypothesis. For example, consider the hypothesis from earlier: 'As the temperature of nichrome wire is increased, the resistance will decrease'. For this to be a valid experiment, it would need to measure the resistance of nichrome wire – it would not be considered valid if it measured the melting point of nichrome wire.

CHECK YOUR LEARNING 0.8

Describe and explain

1 **Explain** the steps of the scientific method.

2 **Describe** what an independent variable is.

3 **Describe** what a dependent variable is.

Apply, analyse and interpret

4 'I can't linearise my data.' **Determine** if this means that your experiment was not valid.

Investigate, evaluate and communicate

5 **Hypothesise** and **create** a methodology for the question 'How does the resistance of nichrome wire change with temperature?'

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  The scientific method
- » Weblink
  Hypotheses
- » Weblink
  Validity and reliability

0.9 The student experiment

KEY IDEAS

In this section, you will learn about:

+ research and planning a student experiment
+ analysis of evidence, interpretation and evaluation
+ communicating findings in a scientific report.

The student experiment is part of the assessment for Senior Physics in Queensland. It involves selecting an experiment that has already been completed in class and modifying it in order to address a hypothesis or research question.

Research question

The purpose of the research question is to guide the direction of the research and analysis. The research question can be developed using five steps:

- Identify the independent variable to be investigated.
- Identify the dependent variable.
- Identify the methodology to be used.
- Draft several research questions.
- Refine and focus one research question.

The statement of the research question will have to be specific and relevant, and should mention the dependent and independent variables. It must show the relationship with the original experiment. For example, 'What is the relationship between the electrical resistance of nichrome wire and its cross-sectional area when temperature, length and alloy composition are kept constant?'

FIGURE 1 The student experiment is part of the assessment for Senior Physics in Queensland.

Developing a rationale for the experiment

The rationale is the **purpose** of the experiment – that is, what the experiment aims to achieve and the **reasons** for conducting the experiment. The reasons for modifying an experiment must include one of:

- a refinement because the original experiment wasn't accurate or precise enough
- an extension where a relationship between two variables was observed but the data didn't extend beyond that range of parameters
- a redirection because a certain natural factor affected results and its relationship to the original variables needs to be assessed.

The rationale needs to describe and explain theoretical relationships for the variables under consideration.

Method

The method must justify how the modifications will refine, extend or redirect the original experiment. It needs to show how the variables will be manipulated and measured, and the other variables controlled.

Manipulating the independent variable

The independent variable can be manipulated by **trials** and **repetitions**. Trials are variations of the independent variable. Five trials should be conducted if it is expected to be a linear relationship. If it is expected to be a non-linear relationship, further trials should be conducted. Repetitions are additional test measurements made under exactly the same methodology, conditions and materials. The more repetitions you do, the less the random error, but three is usual.

Measuring variables

Gather information about how the variables are to be measured. This includes what instrument is to be used, how it works, how it is connected, and what the techniques are for using it and reading it accurately. Uncertainties involved in the measuring process should also be acknowledged. The only variables that should be listed are those that will have an effect on the experiment.

Using a logbook

Using a logbook will help you to record your data accurately as you conduct the experiment. This will make it easier to interpret your results. It can be electronic.

FIGURE 2 Using a logbook will help you record your data accurately.

Reporting the student experiment

The report is the communication of understandings and experimental findings, arguments and conclusions. All scientific reports must include a title that summarises the experiment, and must include the following sections.

Introduction

The introduction must address the research question and hypothesis, and explain the rationale for the experiment.

Method

Study tip

If a table and graph represent the same data, they should share the same name.

The method needs to address the method used in the original experiment and how this has been modified in the student experiment. It should also address management of risk, so that anyone who repeats the experiment can avoid harm. The method should be written as a step-by-step guide so that anyone who wants to repeat the experiment in the future can do so. This means that any descriptions of how to take measurements must be exact, as must the details of how any equipment was used, and the timing of measurements.

Results

The results of the experiment should be presented, but not analysed in this section. Results should be presented using data tables and graphs. A data table should state what has been measured and show raw data that is displayed in forms appropriate for the data. For example, if data about temperature was recorded in Celsius, it should be displayed in Celsius, not kelvin.

Any sample calculations that were conducted should also be represented here. This includes any manipulation of the data, including calculating the average, and calculations of quantities. An appendix can be included to show anything that may not fit into a data table.

Analysis of evidence

Any trends in the data should be apparent after the results section. A relationship between the variables that is applicable to the research question should be identified. The relationship should not be superficial or partial. If the relationship is non-linear, a relationship should be suggested and linearising attempted.

Any limitations of the evidence should also be described here. This will also include an error analysis of the data. Your findings and comparison with theoretical expectations must only be considered within the parameters of the experiment.

Discussion

The discussion is where you interpret the experimental evidence. A justified conclusion can be provided that links to the research question. In this section, you should restate the research question as well as stating if the hypothesis was supported or not.

A summary of the results should be presented to state if the research question was answered. Any evidence or examples used should be specific and relevant. You should explain how each piece of evidence supports the conclusion.

Evaluation of the experimental process

This section is where you discuss the error analysis, including the reliability and validity of the experimental process, using evidence such as the quality of the data. Also, any inconsistent results should be identified. Any anomalies and outliers in data should be discussed and an attempt to explain the source of these should be made. It is important to acknowledge any data that deviates from what was expected.

Suggested improvements and extensions

Any improvements to the design and method must be logically discussed. Issues in the design should be identified and explained. This includes any variables that were not controlled for, such as using the incorrect equipment, or the choice of variables. It is important to explain why these are problems, and how these could be fixed. If there is anything that should be changed in the method, this should also be discussed here.

If there are any extensions to the experiment, or future research possibilities, this should be discussed here. This should be based on critically considering the results of the experiment and the analysis of data.

FIGURE 3 In the discussion a summary of the results should be presented to state if the research question was answered.

Conclusion

The experiment should be summarised and given closure. It should be clear that a logical and reasonable argument has been made from valid and accurate data that is supported by trustworthy and relevant theory to generate logical conclusions.

CHECK YOUR LEARNING 0.9

Describe and explain

1 **Explain** the five steps in developing a research question.

2 **Identify** the three ways a practical can be modified for use in a student experiment.

3 **Recall** whether a hypothesis is mandatory.

Apply, analyse and interpret

4 **Deduce** whether the following scenario is a refinement, extension or redirection: 'Air resistance unexpectedly affected your earlier results and its relationship to the original variables needs to be assessed.'

Investigate, evaluate and communicate

5 **Decide** whether you would include suggestions for overcoming 'mistakes' in the evaluation section of your report. **Justify** whether they fit the definition of improvements or extensions.

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- » Weblink
  Researching a claim

0.10 Research investigation

KEY IDEAS

In this section, you will learn about:

- the purpose of the research investigation
- techniques for evaluating a claim.

The research investigation is a non-experimental task that requires you to evaluate a claim about a significant issue from your study of physics. You will be expected to develop a research question based on possible claims provided by your teacher. Part of the research investigation is obtaining evidence by researching scientifically credible sources. This will form the basis of a justified conclusion about the truthfulness of the claim.

Research and planning

You will need to decide how you want to present your research investigation. There is scope to present this as a report, an essay, a presentation, etc. You may need to consult with your teacher about whether there is a preferred format.

Researching the claim

Select a claim that you understand and that you find interesting. This will make reading through the research easier for you. Once you have selected the claim, identify the key terms and question these terms so you can determine the relationships that exist between variables.

After selecting the claim, read broadly to see if the scientific literature provides evidence for or against the claim. For example, consider the claim, 'When a concert hall warms up, wind instruments go out of tune but stringed instruments do not.' The key terms in this claim could be 'warm up', 'wind/string instruments' and 'tuning'. The relationships between these should link the cause and effect. For example, temperature change (the cause) impacts on the standing waves in strings (the effect).

Preparing for the response

After selecting the claim, you must pose it as a research question. Read through scientific literature and consider the scope and depth of the response. The research questions for the task should consider at least one independent variable, and you will need to consider if this variable is measurable.

Gathering scientific evidence

Approach the scientific literature without a preconceived idea. As you read through the literature, you may find evidence that both supports and refutes your claim. A research investigation must consider the claim as a whole – this means including evidence that is both supportive and against the claim. A good argument considers both sides.

Using credible scientific resources is vital in developing a research investigation. Many scientific reports are available online and you will need to decide if they are credible. A credible article typically is from a scientific journal. Journals that are operated by a university, the government or a research organisation are usually credible sources.

FIGURE 1 Read through scientific literature to gather evidence that supports and refutes your claim.

Interpret the evidence presented in the literature by drawing upon your scientific understanding. This will include separating the evidence that supports your argument from the evidence that contradicts your argument. You will then be able to use the scientific literature to construct an argument. The argument needs to directly answer your research question.

Interpreting scientific evidence

After you have read broadly, you will need to interpret the evidence found in the literature. This will involve looking at results, the methods used, and the way data was collected and analysed across all sources.

Communicate your findings

Once you have conducted the research, you need to present your findings. Regardless of the way your report will be presented, you will need to address the following areas.

Provide an overview

State the claim and provide a rationale for how you developed the research question. This will involve explaining any critical thinking processes that were used during your research and analysis of research.

You must also present your argument and discuss both sides with supporting and refuting evidence. Also explain the physics behind the claim and any cause-and-effect relationships. Using the example of the concert instruments, you may need to explain how sound is made, relevant properties of sound, how standing waves are produced in musical instruments and the effect of changes to these relationships. Explain this using evidence from the literature.

Analysis and interpretation

There are two parts to each argument: analysing the data and interpreting the data.

When you write up your analysis of the data, provide a clear topic sentence that contains sufficient and directly relevant scientific evidence presented in a systematic and accurate way. Any patterns, trends and relationships in the data that support the argument should also be identified. Examine the evidence thoroughly to identify any limitations such as data that is out of date, data that may not be reliable and valid, or data outside of the range of physical conditions specified in the question.

To interpret the data, a topic sentence should include evidence that shows direct links to the claim and the research question. The argument must critically evaluate the validity and reliability of the claim, showing how evidence supports the answer to the research question.

Conclusion and evaluation

The conclusion must consider the limitations identified in the analysis of the data and how these affect the use of evidence to evaluate the claim. The evaluation of the claim should support or refute the claim within the limitations of the evidence identified in the analysis. It should be easily understood and avoid unnecessary repetition.

Any improvements to the investigation should be presented, including limitations of the evidence. Any extensions that would complement the findings of the investigations should be provided, too.

Your research investigation should finish with a strong statement explaining how you have used sound reasoning, and valid and reliable evidence, to support conclusions that directly respond to the claim.

CHECK YOUR LEARNING 0.10

Describe and explain

1 For your research investigation, **explain** whether you have to choose a claim from a list of suggestions or if you can negotiate another.

2 **Define** 'limitations' of the evidence and give an example.

Apply, analyse and interpret

3 **Clarify** whether the claim you have selected for your research investigation has to be true.

Investigate, evaluate and communicate

4 **Create** a relevant research question from the claim, 'The dream of almost limitless clean energy from nuclear power is close to being realised.'

5 **Create** a research question about whether you can travel faster than light using the format, 'To what extent does X affect Y in process Z under stated conditions.'

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The research investigation

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Research

0.11 Preparing for your exams

KEY IDEAS

In this section, you will learn about:

+ how to prepare for your exams
+ exam question strategies.

Being able to understand physics concepts is important – but being able to show it in exams requires different skills. Here we've collected together our best advice.

Managing your study

It can be hard to find time to study, see your friends and family, play sport and work part time. There are several things you can do to keep motivated and focused during your senior years:

- A study timetable – this can help you plan ahead and see what your week looks like. Assigning specific time slots to your subjects can help you balance your week.
- To-do lists – to-do lists can help you see what you need to achieve in a shorter time period. They can also motivate you to keep working, as you can see what you have already achieved.
- Study environment – create a study environment that you feel comfortable in. This could be your desk at home, school or local library, or anywhere that you feel ready to study. Ensure there are no distractions, and that you have everything you could need such as a calculator, spare paper and pens.
- Avoid distractions – when you set aside time to study, it is good to use that time wisely. Try to turn your phone off, not have TV or music on in the background, and not to have too many snacks to distract you.
- Reward yourself – as much as it is important to study during your senior years of high school, this does not mean you should neglect other areas of your life. You can reward yourself by catching up with friends, watching an episode of your favourite TV show or going out for coffee. Whatever you enjoy doing can motivate you to keep studying.

FIGURE 1 Multiple-choice questions will be part of your examinations.

Participate during the year

Throughout the year you will have many opportunities for revision and to carry out experiments. It is important to be an active participant in all of these, as they will help you prepare for your examinations. By participating in experiments, you will become more familiar with the variables, the names of different apparatus, the rate at which variables change, and which variables are important. This will help with data tests, as well as making you more comfortable when a question about the topic comes up in your exam.

In the exam

Multiple-choice questions

Multiple-choice questions will be part of your examinations. Typically, multiple-choice questions follow a structure with one answer that is definitely wrong, one that is partially correct but has a word in it that makes it incorrect, one that may be true but is irrelevant to the question, and one correct answer.

While there can be a pattern to multiple-choice questions, there is no guarantee that this will be followed. It is important that you always read each option carefully to determine which is the correct answer.

Developing automaticity

Expert problem-solvers often have an automatic approach to the first stages of a problem. By practising with lots of simpler one-concept and one-star questions throughout this text, you are developing an automatic approach to dealing with concepts and formulas. For example, if you see voltage and current, the automatic approach would be to immediately think 'Ohm's law', $V = IR$, and you would calculate resistance. If you have already thought of this at the beginning of a question, you will have more time to focus on the more difficult aspects.

The 7F approach to problem-solving

1 Focus

People often start solving problems without realising what topic they are working in. It is important to have your mind focused on the right field or topic. For example, you may need to determine if you are working on linear motion or waves – both of these topics have velocity, displacement and time. To determine which topic you are working in, look for key words and then narrow down your thinking.

2 Facts

When you are looking at questions, it is important to look for facts. You should look for any **numerical data** in the question – circle this and put a symbol next to it. You should then look for any **non-numerical data** in the question, such as 'starts at rest', 'boiling point' or 'air to glass'. These terms will provide information about the topic – circle these words and annotate what they mean. Finally, look for **key words** that express the limitations of the data, such as 'smooth', 'uniform' or 'constant'.

3 Find

Locate the part of the question that says what you have to find. Note exactly what the physical quantity is and any units it has to be expressed in.

4 Figure

Drawing a figure can help you sort out the data. If you draw a figure, make sure it is clear so that you can sort the data easily.

5 Formula

Start by identifying the formulas you think may be appropriate. Think about what symbols are in the data and match them with the symbols from the formula. For simpler questions there may be one unknown, so you will need to find a formula that has data for every quantity except one. Irrelevant information is also added into questions to force you evaluate what is needed. For harder questions, you may need two or more formulas. For example, to calculate work you can use $W = Fs$, but first you may have to calculate force using, $F = ma$.

6 Figure it out

- Spread out your working and do it in a single column.
- Work as neatly as you can – this makes it easy to check your equations and formulas as you work through the problem.
- Rearrange the formula to have the unknown as the subject of the equation.
- Work in symbols for as long as you can – this makes calculation and transcription errors less likely.
- Keep symbols clear – for example, write u and v neatly, don't confuse m and M, and don't confuse t and T.
- Make sure your calculator is in the right setting – degrees or radians (depending on the question).
- Use your own familiar calculator that you usually use for physics – don't use an unfamiliar calculator at the last minute.
- Try to work in scientific notation – long lists of zeros after the decimal point can lead to errors.
- Don't skip steps – write each step down so it is easier to check later and, if needed, find your error.
- Remember mathematics rules – for example, if you multiply a negative by a negative, it will be positive.

7 Finish

- Check your arithmetic.
- Should the answer really be negative?
- Put the answer back into the original equation to check.
- Have you answered the question? For example, if the question asks for the height of a cliff, don't leave the answer as $s = -150$ m. Finish your answer by writing 'height = 150 m'.
- Check that you have expressed the answer in the correct units.

Responding to cognitive verbs

During assessment tasks and examinations, you will be presented with **cognitive verbs**. Cognitive verbs are task words that will provide information on what you are expected to provide in an answer to a question.

It is important that you understand the difference between different task words. For example, as question that asks you to compare is different to one that asks you to contrast. One requires you to show similarities and differences, while the other is only asking to show the differences.

If you understand exactly what a cognitive verb is asking for, you can provide exactly what the examiner is looking for. Examiners want to award you marks, but can only do so if a you provide the correct information. For example, if you describe data in your answer, but do not analyse the data, you will not be eligible for full marks.

You may also encounter cognitive verbs that have multiple definitions. It is important that you are able to identify which definition is appropriate to the question.

Below is a sample of cognitive verbs that may come up throughout this book and in your assessments, a full list of QCAA cognitive verbs is provided on your obook assess.

TABLE 1 Some of the cognitive verbs used in the book

Cognitive verb	Definition	Sample question
Analyse	Dissect to ascertain and examine constituent parts and/or their relationships; break down or examine in order to identify the essential elements, features, components or structure; determine the logic and reasonableness of information; Examine or consider something in order to explain and interpret it, for the purpose of finding meaning or relationships and identifying patterns, similarities and differences	Using your understanding of weight and mass, **analyse** why it is easier to lift people in a swimming pool but why a rubber brick may still feel heavy.
Apply	Use knowledge and understanding in response to a given situation or circumstance carry out or use a procedure in a given or particular situation	A pulse seems to increase in speed when it is going from one spring to another. **Apply** your understanding of speed, frequency and wavelength to deduce whether a pulse would be going from a light to heavy spring, or the reverse.
Assess	Measure, determine, evaluate, estimate or make a judgment about the value, quality, outcomes, results, size, significance, nature or extent of something	**Assess** the effect on their experiment if students noticed that some of the loops in the coil were touching each other.
Calculate	Determine or find (e.g. a number, answer) by using mathematical processes; obtain a numerical answer showing the relevant stages in the working; ascertain/determine from given facts, figures or information	**Calculate** the resistance of a 50 m length of silver wire of cross-sectional area 0.50 mm^2 at 20°C.
Compare	Display recognition of similarities and differences and recognise the significance of these similarities and differences	**Compare** free convection and forced convection.
Communicate	Convey knowledge and/or understandings to others; make known; transmit	**Communicate** the findings through a table and graph.
Consider	Think deliberately or carefully about something, typically before making a decision; take something into account when making a judgment; view attentively or scrutinise; reflect on	**Consider** what the forces would be if a mass of 500 kg was placed on the table.
Deduce	Reach a conclusion that is necessarily true, provided a given set of assumptions is true; arrive at, reach or draw a logical conclusion from reasoning and the information given	**Deduce** how much heat transfer occurs from a system if its internal energy decreased by 350 J while it was doing 50 J of work.
Describe	Give an account (written or spoken) of a situation, event, pattern or process, or of the characteristics or features of something	**Describe** the type of decay where there is a surplus of protons.
Design	Produce a plan, simulation, model or similar; plan, form or conceive in the mind	**Design** an experiment to investigate the intensity of light through a pair of polarisers as one of the polarisers is rotated through 180°.
Determine	Establish, conclude or ascertain after consideration, observation, investigation or calculation; decide or come to a resolution	**Determine** the amount of C-14 as a percentage of the C-14 in living tissue if it really was from 30 CE.
Discuss	Examine by argument; sift the considerations for and against; debate; talk or write about a topic, including a range of arguments, factors or hypotheses; consider, taking into account different issues and ideas, points for and/or against, and supporting opinions or conclusions with evidence	**Discuss** the problems associated with using the Fahrenheit scale given that the United States is one of the few countries in the world to still use it.

Cognitive verb	Definition	Sample question
Distinguish	Recognise as distinct or different; note points of difference between; discriminate; discern; make clear a difference/s between two or more concepts or items	**Distinguish** between the nuclear strong force and the electrostatic (Coulomb) force.
Explain	Make an idea or situation plain or clear by describing it in more detail or revealing relevant facts; give an account; provide additional information	**Explain** what it means to have a fission chain reaction.
Interpret	Use knowledge and understanding to recognise trends and draw conclusions from given information; make clear or explicit; elucidate or understand in a particular way; Identify or draw meaning from, or give meaning to, information presented in various forms, such as words, symbols, pictures or graphs	**Interpret** the data and plot the shape of the spring at $t = 0$.
Investigate	Carry out an examination or formal inquiry in order to establish or obtain facts and reach new conclusions; search, inquire into, interpret and draw conclusions about data and information	**Investigate** the following question: was the strong nuclear force 'invented' in the 1970s or was it 'discovered'?
Justify	Give reasons or evidence to support an answer, response or conclusion; show or prove how an argument, statement or conclusion is right or reasonable	**Justify** the conclusion that the collision was elastic.
Predict	Give an expected result of an upcoming action or event; suggest what may happen based on available information	Use the wave equation to **predict** the velocity of a refracted wave if its incident speed is 30 cm s^{-1} and wavelength 3 cm, if its refracted wavelength is 2 cm.
Propose	Put forward (e.g. a point of view, idea, argument, suggestion) for consideration or action	**Propose** a reason for why many people die in intense bush fires without being touched by the flames.
Sketch	Execute a drawing or painting in simple form, giving essential features but not necessarily with detail or accuracy; In mathematics, represent by means of a diagram or a graph; the sketch should give a general idea of the required shape or relationship and should include features	**Sketch** the following vector quantities on a directed number line; 30 m E and 100 m W.

Source: *Physics 2019 v1.2 General Senior Syllabus Queensland Curriculum & Assessment Authority*

CHECK YOUR LEARNING 0.11

Describe and explain

1 **Create** your own study timetable, including any other commitments such as sport, work, volunteering and social activities.

2 **Create** a list of things that you need to study.

3 Think about what distracts you. **Identify** these and things write them down so you can create an environment free from distraction.

4 **Explain** the 7 Fs of problem-solving.

Check your obook assess for these additional resources and more:

» **Student book questions**
Check your learning 0.11

» **Video**
Preparing for exams

» **Increase your knowledge**
Creating a study timetable

» **Weblink**
QCAA Senior Physics Syllabus

CHAPTER 0

Review

Summary

0.2
- There is an international system of units called SI that is most commonly used around the world and by scientists.
- Measurable features or properties of objects are often called physical quantities. All physical quantities should be quoted with their numerical value and their unit.

0.3
- Significant figures are those digits in a number that are known with certainty plus the first digit that is uncertain.

0.4
- All measurements include errors or uncertainties, either systematic or random.
- Uncertainties in calculations of experimental results can be determined using rules for propagation.

0.5
- Precision is a measure of the uncertainty of experimental results – it is expressed as absolute or percentage uncertainty.

0.6
- Graphs have two axes. The *x*-axis (the horizontal axis) is for the independent variable or cause. The effect of that cause is plotted on the *y*-axis (the vertical axis) and is called the dependent variable.
- The slope or gradient of the line is defined as change in *y* divided by change in *x*. This is often called 'rise over run'.
- Common terms associated with graphs are: direct proportion, proportion (which includes linear and parabolic relationships) and indirect proportion.
- Graphs of the following relationships have characteristic shapes that have been detailed in this chapter: $y \propto x$, $y = mx$, $y = mx + c$, $y \propto x^2$, $y \propto \frac{1}{x}$, $y \propto x^{\frac{1}{2}}$, $y = y_0 e^{-kt}$.
- Relationships between variables can be proven by plotting the predicted function of *x* on the *x*-axis and examining to see whether the graph is a straight line. This is called linearising.
- Graphs can be used to detect and show errors in experimental results.

0.7
- The line of best fit for a graph should pass through as many points as possible. For the points that are off the line, there should be an equal number of points above the line and below it.
- Points a long way from the line of best fit are called anomalies or outliers.

0.8
- The scientific method is a process of investigation with eight steps.
- Scientific reports are presented with an introduction, research question, hypothesis, method, discussion and conclusion.

Key terms

- accuracy
- anomaly
- best estimate
- dependent variable
- independent variable
- linearising
- maximum line of best fit
- minimum line of best fit
- outlier
- percentage uncertainty
- precision
- random errors
- reliability
- reliable
- scale reading limitations
- scientific notation
- significant figures
- standard deviation
- systematic errors

Key formulas

Absolute error	$E_a = \|X_O - X_A\|$
Determining slope of a graph	Slope $(m) = \frac{\text{change in } y}{\text{change in } x} = \frac{\Delta y}{\Delta x} = \frac{y_2 - y_1}{x_2 - x_1}$
Absolute uncertainty of the mean	$\delta x = \pm\frac{(x_{max} - x_{min})}{2}$ $\delta\% = \frac{\delta X}{X_0} \times 100\%$
Percentage uncertainty	Percentage error $(E\%) = \frac{\text{measured value} - \text{true value}}{\text{true value}} \times 100\%$
Percentage error	$E\% = \frac{E_a}{X_A} \times 100\%$

Revision questions

The relative difficulty of these questions is indicated by the number of stars beside each question number: ★ = low; ★★ = medium; ★★★ = high.

★★ Short answer

Describe and explain

★ **1** **Classify** the following units as SI or non-SI: metres, kilograms, pounds, kelvin.

★ **2** **Explain** the difference between significant figures and scientific notation.

★ **3** **Explain** what a 'systematic error' means in terms of zero error.

★ **4** **Explain** what is meant by 'propagation of errors' when performing a calculation.

★ **5** **Explain** why is it necessary to calculate percentage error of a result rather than just leave it as absolute error.

★ **6** **Calculate** the following:

a 1.25 cm converted to metres

b 143 367 mm converted to metres

★ **7** **Identify** the number of significant figures in each of the following:

a 83.83 **b** 20.0

★ **8** **Express** the following in scientific notation:

a 0.000 552 **b** 73 000 000

★★ **9** **Calculate** the following and express in scientific notation to the correct number of significant figures:

a 1.18 cm × 3.1416 cm

b $(2.0 \times 10^{-3}$ m$) \times (2.0 \times 10^{-4}$ m$)$

Apply, analyse and interpret

★★ **10** **a** **Sketch** a graph of the data given in Table 1 and draw a line of best fit. (Note: the independent variable is listed first.)

TABLE 1

Time (s)	0.0	2.0	4.0	6.0
Distance (m)	0.0	12	23	37

b For the line plotted on the graph:

i **calculate** the slope

ii extrapolate to 8.0 seconds

iii interpolate for 3.0 s

★★ **11** An experiment using an electric water-heater was conducted to test the effect of different currents on the heat added to a cup of water after 10 minutes. The results are in Table 2.

TABLE 2 Results of water heating experiment

Current , I (A)	0.5	0.8	1.0	1.6	2.4	3.0
Heat, Q (J)	375	960	1500	3800	8640	13 500

a **Construct** a graph to show the relationship between heat Q in joule, developed in a heater by electric currents of *I* ampere.

b **Describe** the relationship between Q and I.

c **Construct** a linearised graph to confirm the relationship between Q and I.

★★ **12** An analogue voltmeter with a scale division of 0.1 V reads 2.4 V when placed across a resistor of 47 Ω ± 5%.

a **Determine** the absolute uncertainty in the voltage reading.

b If a calculation of $\frac{V^2}{R}$ was made, **calculate** the percentage uncertainty in the result.

★★★ **13** As part of an investigation into motion of a falling object, a tennis ball was dropped from various heights as shown in Table 3 over the page. The heights were measured with a metre ruler marked in mm and the uncertainty was considered insignificant. Times for three trials were measured with a stopwatch.

TABLE 3 Drop heights and times

Trials	Drop time t (s)		
Height, s (m)	Test 1	Test 2	Test 3
0.50	0.37	0.44	0.50
1.00	0.62	0.56	0.56
1.50	0.75	0.75	0.69
2.00	0.75	0.87	0.94

- **a** **Calculate** the mean ($\bar{x}$), and the absolute uncertainties of the mean for the times for each height.
- **b** **Construct** a graph with height (s) on the horizontal axis, and the corresponding mean of the times on the vertical axis.
- **c** **Construct** a linearised graph by plotting $\sqrt{s}$ on the horizontal axis and t on the vertical axis. Add vertical error bars.
- **d** **Determine** the gradients of the maximum and minimum lines of best fit, and express these as an absolute uncertainty for the mean value of the gradient.

★★★ **14** German physicist Arnd Leike, from the University of Munich, found that the decay of foam height in beer with time was exponential: $y \propto \frac{1}{x^n}$, where y = height of the foam and x = time. He was awarded an 'Ig Nobel' Prize by the science humour magazine Annals of Improbable Research for one of the world's most useless pieces of research. Using an Excel spreadsheet or your graphing calculator, **describe** and **determine** the difference between the graphs when $n = 3$ (Leike's result) and $n = 2$ (inverse square).

★★★ **15** In the automobile sport of drag racing, the aim is to cover a one-quarter mile (402 m) track in the shortest time possible – typically 5 to 10 seconds. The more powerful the engine, the faster the final speed and the shorter the time. However, you can't just keep increasing the power and expect significant gains. In fact the rule of thumb says the final speed is a cube root function with power. The equation is: $v = 14.8\sqrt[3]{P}$ where v is the final speed in miles per hour (mph), and P is the engine output in horsepower (hp).

The 426 cubic inch aluminium Chrysler Hemi is a supercharged, fuel-injected, nitromethane-burning engine that produces a massive 8000 hp (horsepower).

TABLE 4 Speed vs power using a Chrysler Hemi engine

Power (hp)	7000	8000	9000	10000	11000
Speed (mph)	283	296			

- **a** **Determine** the missing values from Table 4 by applying the formula given.
- **b** **Construct** a graph with power on the horizontal axis and final speed on the vertical axis.
- **c** **Construct** a linearised graph based on the expected relationship as described in the formula.

★★★ **16** The magnitude (M) of an earthquake is measured using the Richter Scale. The scale was developed in 1935 by US seismologist Charles Richter. Because the range of energy involved in earthquakes ranges from very small to enormous, the scale uses this relationship:

$$M = \frac{2}{3}\log_{10}\left(\frac{E}{E_0}\right)$$

where E is the energy of the earthquake and E_0 is the energy of a reference earthquake (10^{44} J). It is not used much any more in scientific circles.

- **a** **Identify** the type of relationship this is (linear, power, exponential, logarithmic)
- **b** **Calculate** M for an earthquake having an energy output of 10^{45} J.
- **c** Now **determine** the magnitude (M) for earthquakes having energy E of 10^{46}, 10^{47}, 10^{48}, 10^{49} J and enter into a table as shown. Calculate $\log\left(\frac{E}{10^{44}}\right)$. The first two have been done for you:

TABLE 5 Energy and magnitude of Earthquakes

Energy (J)	10^{45}	10^{46}	10^{47}	10^{48}	10^{49}
$\log_{10}(E/10^{44})$	1	2			
Magnitude (M)	0.67	1.33			

- **d** **Sketch** M (y-axis) vs $\log_{10}\left(\frac{E}{10^{44}}\right)$ on the x-axis. Is it linear? (You could have plotted M vs E using Excel but it is too awful a shape to contemplate).

★★★ **17** **Determine** the reading and uncertainty of the measurement on the ruler in Figure 1. The numbers are centimetres and the small divisions are millimetres.

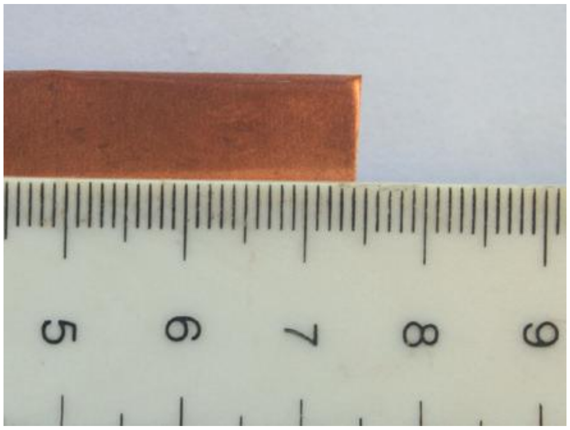

FIGURE 1 What is the reading and uncertainty of the measurement?

Investigate, evaluate and communicate

★★ **18** The following sets of data represent common relationships in physics. **Predict** the relationship by graphical means for each and confirm it where necessary by linearisation.

a **TABLE 6**

x	1	2	3	5	6
y	2.00	1.10	0.67	0.41	0.33

b **TABLE 7**

x	1	2	4	6	8
y	3.00	0.75	0.19	0.08	0.05

c **TABLE 8**

x	0	2	3	5	7
y	0	20	45	125	245

★★★ **19** The following sets of data represent common relationships in physics. **Predict** the relationship by graphical means for each and confirm it where necessary by linearising.

a **TABLE 9**

x	0.50	1.70	2.10	3.60	7.00
y	0.54	0.99	1.10	1.44	2.01

b **TABLE 10**

x	0	1.5	3.4	5.1	7
y	3.2	9.2	16.8	23.6	31.2

★★★ **20** Students were investigating the swing of a pendulum as a function of length of the string. Their results are shown in Table 11. The period is the time for one complete swing.

TABLE 11 Results of a pendulum experiment

Length, L (m)	Period, T (s) ± 0.15 s
0.10	0.78
0.20	1.20
0.40	1.42
0.60	1.90
0.80	2.04
1.00	2.16
1.20	2.50
1.40	2.67

a **Construct** a graph with length on the horizontal axis and time on the vertical axis.

b **Predict** the relationship between T and L.

c **Construct** a linearised graph to confirm the relationship.

d **Determine** the gradient of the line of best fit.

e **Construct** error bars on the graph and determine the gradient of the maximum and the minimum lines of best fit.

f **Express** the gradient as a mean value ± absolute uncertainty.

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Chapter 0

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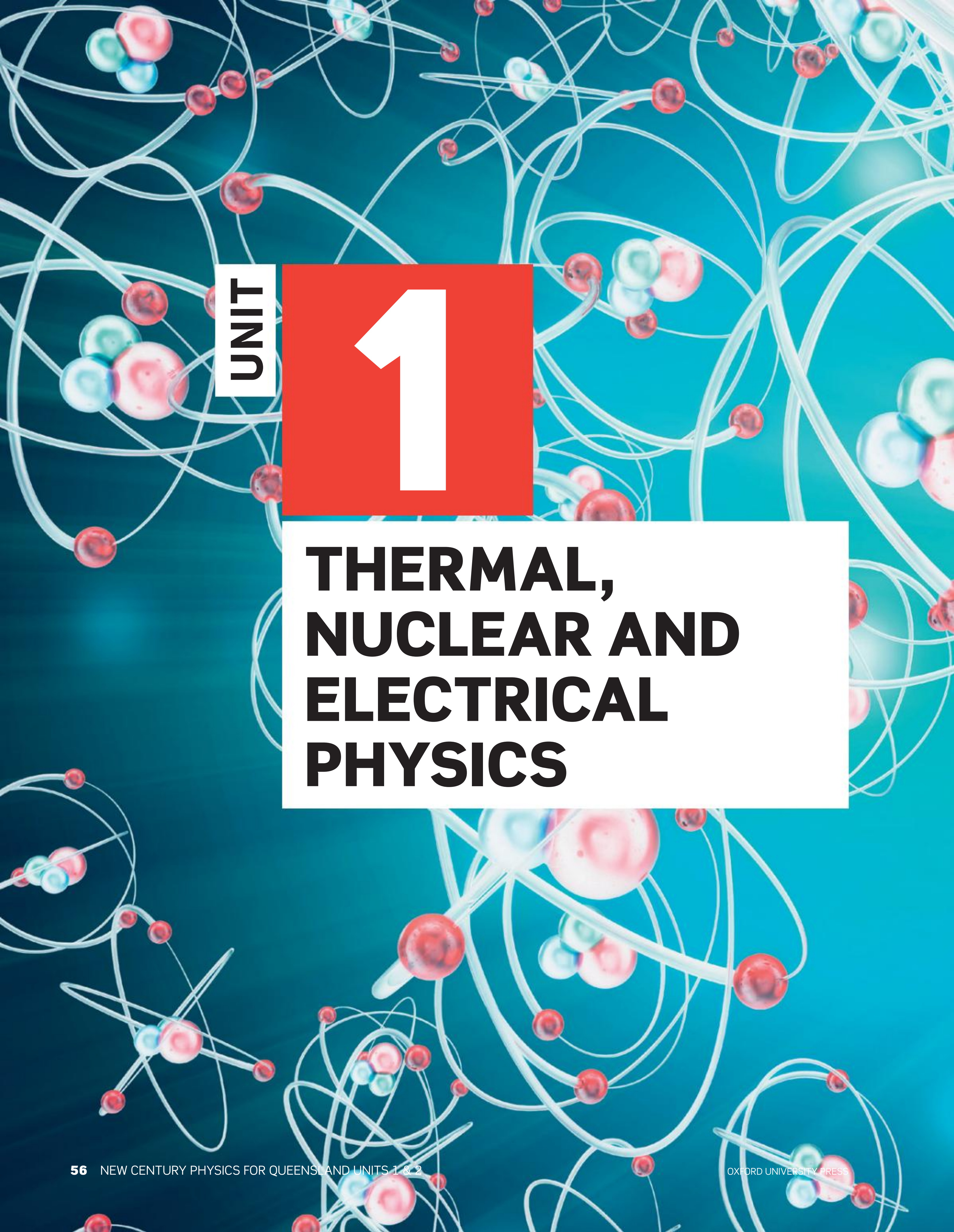
» Flashcard glossary
Chapter 0



UNIT 1

THERMAL, NUCLEAR AND ELECTRICAL PHYSICS

The three seemingly different ideas of heat, nuclear energy and electricity have one thing in common – the pivotal role of energy in modern society. These three topics provide an introduction to the fundamental idea of energy transfers and transformations and how global energy needs are met.

As objects are heated, their energy increases, and this means changes to their internal energy – the microscopic kinetic and potential energy of the particles. An understanding of this internal energy forms the basis of modern thermodynamics and the laws that allow us to predict the direction of the flow of energy, deduce the source of energy losses and calculate the efficiency of energy transfer in devices such as car engines, steam engines and refrigerators.

This leads into an examination of matter at the atomic scale, starting with the structure of the nucleus and how the strong nuclear force and electrostatic forces compete to keep the nucleus together or let it disintegrate into alpha, beta and nuclear radiation along with neutrinos and anti-neutrinos. We see how a decaying nucleus converts mass into energy as described by Einstein's famous equation $E = mc^2$ and how this process is the basis for nuclear reactors, radiopharmaceuticals and the stars. The final topic looks at electricity, beginning with the relationship between voltage, current and resistance. Use of circuit analysis helps us understand how electrical energy is transferred in wires to be used and controlled in homes and workplaces.

UNIT 1 TOPICS

Topic 1 – Heating processes	Chapters 1–3
Topic 2 – Ionising radiation and nuclear reactions	Chapters 4–6
Topic 3 – Electrical currents	Chapters 7–9

Unit objectives

→ Describe and explain heating processes, ionising radiation and nuclear reactions, and electrical circuits.

→ Apply understanding of heating processes, ionising radiation and nuclear reactions, and electrical circuits.

→ Analyse evidence about heating processes, ionising radiation and nuclear reactions, and electrical circuits.

→ Interpret evidence about heating processes, ionising radiation and nuclear reactions, and electrical circuits.

→ Investigate phenomena associated with heating processes, ionising radiation and nuclear reactions, and electrical circuits.

→ Evaluate processes, claims and conclusions about heating processes, ionising radiation and nuclear reactions, and electrical circuits.

→ Communicate understandings, findings, arguments and conclusions about heating processes, ionising radiation and nuclear reactions, and electrical circuits.

Source: *Physics 2019 v1.2 General Senior Syllabus Queensland Curriculum & Assessment Authority*

FIGURE 1 This image is a representation of atomic structure. Atomic reactions are the basis of the different forms of energy.

CHAPTER

1 Heat and temperature

Would you rather be too hot or too cold? If you're too hot, you can sit in the shade or wear fewer clothes, but that's about it. If you're too cold, you can add extra layers of clothing. But what is more important to survival: heat, or the lack of heat? The answer to each of these questions has to do with the internal structure of matter and how it responds to heat. It's a subject called 'thermodynamics'.

The term 'thermodynamics' stems from the Greek *therme* meaning 'heat' and *dynamis* meaning 'power', which was appropriate for the 1800s when it was first used as people were concerned about how to convert heat into power for factories and mines. Today, we say that thermodynamics is concerned with systems involving energy transfer in the form of heat and work. This includes applications such as solar heating and cooling of buildings, refrigeration and air-conditioning, and the design and construction of engines. To understand how matter behaves when heated, we need to consider the makeup of matter in terms of its particles.

OBJECTIVES

→ Describe the kinetic particle model of matter.

→ Define and distinguish between thermal energy, temperature, kinetic energy, heat and internal energy.

→ Use $T_K = T_C + 273$ to convert temperature measurements between Celsius and Kelvin.

Source: *Physics 2019 v1.2 General Senior Syllabus Queensland Curriculum & Assessment Authority*

FIGURE 1 Why is it cooler in the shade?

MAKES YOU WONDER

In this chapter we will be examining some aspects of atoms that will help to answer questions such as:

→ What is heat? People talk about 'heat flow', but what flows?

→ Heat from the Sun and the cold of winter have always affected living conditions. What sense is more important for survival: the ability to feel heat and cold, the ability to see light, or the ability to hear sound? If you had to lose one, which one would it be?

→ Why does sucking an ice block make you feel cool? How does a cold tongue cool you down?

→ On a very hot day at the beach, why does walking on dark sand burn your feet but white sand is okay?

→ How can someone walk barefoot on coals at 400°C but standing on a hot road at 60°C burns their feet?

→ It is said that water molecules vibrate, but have you ever seen the molecules vibrate?

→ Temperature change initiates breathing when a child is born, so why are delivery rooms heated? Shouldn't delivery rooms be cold so the reflex works even better?

→ Why can you smell if a gas tap has been left on when you walk into a laboratory, but you cannot smell the water spilt on the bench?

→ What's the hottest place on Earth, and what's the coldest? What are the maximum and minimum temperatures ever recorded experimentally on Earth?

→ Are heat and temperature the same thing? More heat leads to a higher temperature. What do they have in common?

→ Which has more heat: a cup of coffee or a swimming pool?

→ Do heat and cold flow like liquids? Heat seems to 'run' from hot to cold. What do hot temperature and cold temperature have in common with a liquid?

PRACTICALS

MANDATORY PRACTICAL	**1.1** Heating water on a hotplate – graphing and analysing data
SUGGESTED PRACTICAL	**1.2** Precision and accuracy of thermometers

MANDATORY PRACTICAL

1.1 Heating water on a hotplate – graphing and analysing data
Go to page 476 »

1.1 Heating and cooling

KEY IDEAS

In this section, you will learn about:

+ the definition of heat and energy
+ how we feel heat.

heat
the internal energy transferred throughout the heating process

energy
the capacity to do mechanical work (symbol: W; SI unit: joule; unit symbol: J)

The focus of this chapter is both the term **heat** and various forms of **energy**, such as thermal, kinetic and internal, and its effect on matter.

Heat is energy in the process of being transferred from one place to another due to temperature difference. Because heat, like 'work', is a quantity of energy being transferred between two bodies, neither body has a definite amount of heat. Instead, they have a definite amount of energy. In the same way, a body doesn't have a certain amount of 'work'. It has energy, and when it transfers this energy we say work is being done. 'Heat' is not a thing – it is a process. Energy is the capacity to do work. The higher the energy content, the greater the effect when it is transformed or transferred.

The idea of heat has developed through three different models over time. Thousands of years ago, heat was thought to be something alive and living inside things. This was the animistic (animal-like) view. This changed 2000 years ago with the Greek substantialist idea that heat was a material substance (called 'caloric') that was lost or gained as an object was heated or cooled. Our modern kinetic view started in the mid-1800s when heat came to be regarded as the transfer of energy related to the movement of microscopic particles (atoms and molecules). The word 'energy' was given in 1852 by William Thomson (Lord Kelvin, 1824–1907) from Glasgow, Scotland. This is where we are today: 'energy' is not a thing – it is a property of an object.

How do we 'feel' heat?

Steam feels hot, but ice feels cold. We have receptors (called thermoreceptors) in our skin that tell us if something is hot or cold. The breakthrough research on this was done by New Zealand scientist Dr Ainsley Iggo in 1959. He anaesthetised 15 cats and exposed the nerves in their legs. By placing hot and cold metal pins on certain nerves he found that there were different receptors for hot and for cold. The hot ones had a thin myelin sheath on the axon so the electrical signal to the spinal cord was slow. The cold ones had a thicker sheath and the signals were faster. That's why you respond faster to a cold stimulus than a hot one.

CHECK YOUR LEARNING 1.1

Describe and explain

1 **Describe** the difference between heat and energy.

2 **Explain** why heat is described as a process.

3 **Describe** how we feel heat.

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1.1 Heating water on a hotplate–graphing and analysing data

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» Weblink
Why do some people feel the cold more?

SUGGESTED PRACTICAL

1.2 Precision and accuracy of thermometers
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1.2 The kinetic particle theory of matter

KEY IDEAS

In this section, you will learn about:

+ the kinetic particle theory of matter
+ the characteristics of solids, liquids and gases as states of matter.

atoms
the smallest particle of a chemical element that can exist

We take it for granted that matter is made of **atoms**. The earliest people to make this claim were the Greek philosophers Leucippus and Democritus (about 2500 years ago), who suggested that matter consisted of small, hard particles that couldn't be cut up. They called the particles atoms (Greek *a* = 'not', *toma* = 'cut'). This idea of particles gave rise to what we know as solids, liquid and gases – the three states of matter, sometimes called the three 'phases' of matter.

States of matter

Solids, liquids and gases feel different and behave differently. They can be hard, soft, runny or invisible. They can blow like the wind, flow like a river or just sit still. An understanding of how particles are arranged in the states of matter can help us understand their properties – in this case, what happens when they get hot, or when hot and cold are mixed. Figure 1 shows a simple diagram of the three states of matter. But to make sense of their properties we need to look at each state in detail.

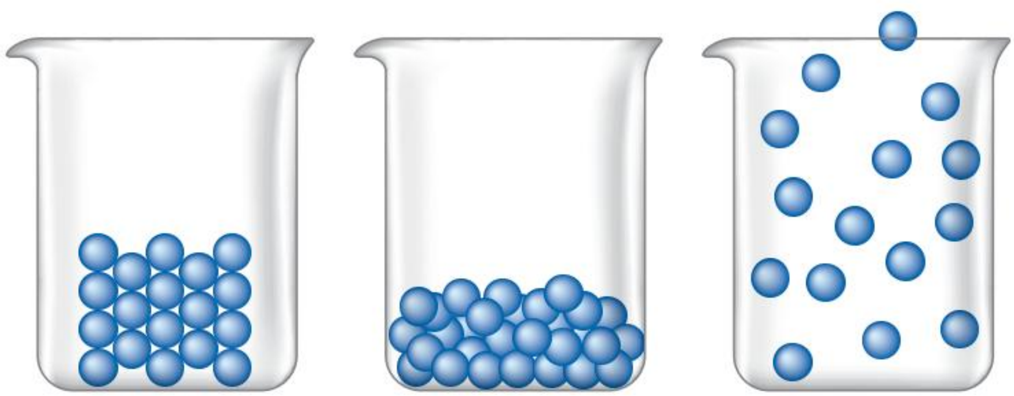

FIGURE 1 The three states of matter.

Solids

potential energy
stored energy found in the chemical bonds and nucleus of a substance

Particles in solids are held very closely together by strong bonding forces. Microscopic **potential energy** comes from separation against these attractive forces. In a solid the particles have very little separation, so the microscopic potential energy is low. We call it microscopic potential energy ($E_{p(micro)}$) to distinguish it from the bulk, or macroscopic, potential energy you would have learnt about in Year 10, when you held a ball in the air ready to drop and time its fall. The strong bonding forces make solids very difficult to break apart. The particles don't move around from place to place but simply vibrate

kinetic energy
the energy due to the motion of an object, including the motion of particles in a substance (symbol: E_K; SI unit: joule; unit symbol: J)

particle
a minute portion of matter, when associated with the kinetic model they are mainly atoms and molecules

in their spot. This vibration means they have **kinetic energy** (also known as microscopic kinetic energy ($E_{k(micro)}$) as well.

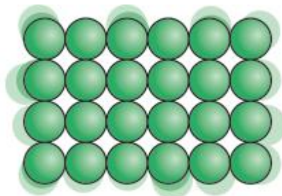

FIGURE 2 Particles in a solid are close together and can't move around. The arrangement is called a 'lattice'. Solids keep their own volume and shape when placed in a container.

Liquids

Particles in liquids are quite close, but the bonding forces between the particles are not as strong as in solids so they can slide past one another. The energy that was used to overcome the strong bonds of the solid phase means they have more microscopic potential energy than solids. Because the particles can move from place to place, we say they have translational motion (Greek *trans* = 'across', *lato* = 'to carry'). This gives them more kinetic energy. They can also have rotational motion, which means they can spin on their own axis. So long as they are not monatomic (single atoms like helium), they will have some rotational kinetic energy – but only a small amount. Water (H_2O) and ethanol (CH_3CH_2OH) are common laboratory examples of molecules with translational and rotational kinetic energy.

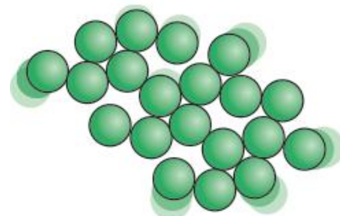

FIGURE 3 Particles in a liquid are close together and can move around. Liquids keep their own volume but take on the shape of the container they are placed in.

Can you compress a liquid? The answer is yes. You can compress liquids, even water, or almost any material. However, it requires a great deal of pressure to accomplish a little compression. For that reason, liquids and solids are sometimes referred to as being incompressible.

FIGURE 4 Water is a common laboratory example of a substance containing molecules with translational and rotational energy.

Gases

Particles in gases move around very quickly with a lot of space between them. The particles bounce off each other. The intermolecular forces are quite weak, and the energy used to overcome the bonds of the liquid phase means they have more microscopic potential energy than liquids. But because they move at high speeds and rotate, they have considerable translational energy as well as the existing vibrational and rotational energy. Monatomic gases such as helium (He) of course don't have rotational energy – just translational.

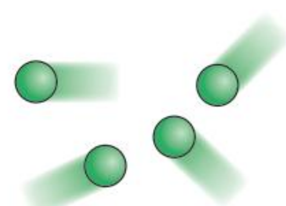

FIGURE 5 Particles in a gas are far apart and can easily move around. Gases take on the volume and shape of the container they are in.

Energy in the states of matter

If you have a solid, such as ice, you can add heat energy and it changes phase to become water. If you add more heat energy, it changes phase to become steam. That means steam has more energy than water, which has more energy than ice.

Kinetic theory

The kinetic molecular theory of matter accounts for the properties of matter in its three different phases. A simple statement of the model is:

- Matter is made up of particles that are constantly moving.

  As a consequence of this, we can also say:
- Matter is made up of small particles (atoms or molecules) that are in constant random motion.
- There are large spaces between particles. The potential energy is related to the separation distance.
  - In a gas, the separation distance between particles is very large in comparison to their size so there are no attractive or repulsive forces between them.
  - In a liquid, the particles are still far apart but they are close enough that the attractive forces pull them together.
  - In a solid, the particles are so close that the forces of attraction confine the particles to a particular shape.
- Particles have energy. The temperature of a substance is a measure of the average kinetic energy of the particles.
- Collisions between particles are perfectly elastic ('elastic' means they do not lose kinetic energy when they collide).

TABLE 1 Summary of physical properties of states of matter

	Solids	Liquids	Gases
Volume	keep own volume	keep own volume	take volume of container
Shape	keep own shape	take shape of container	take shape of container

CHECK YOUR LEARNING 1.2

Describe and explain

1 **Identify** the main assumptions of the kinetic particle model.

2 **Explain** how the kinetic energy of a substance changes as it goes from a solid to a liquid to a gas. (You learnt about kinetic energy in Year 10.)

Apply, analyse and interpret

3 **Deduce** the microscopic nature of solids and liquids given that they can't be compressed very much. It takes large forces to compress them even slightly.

4 **Derive** a conclusion about the microscopic nature of gases given that they are very compressible compared with solids and liquids.

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- » Weblink
  Kinetic particles
- » Weblink
  States of matter

1.3 Temperature and kinetic energy

KEY IDEAS

In this section, you will learn about:

+ macroscopic energy and microscopic energy
+ internal energy.

As well as kinetic and potential energy, there are two more energy terms that are important. It is essential that you know what they are and how they are different.

As mentioned before, objects can be considered to have their energy as two types: **macroscopic energy** and **microscopic energy**. Macroscopic energy is the sort of energy you dealt with in Year 10. If you threw a stone off a cliff, you would say that the rock has gravitational potential energy $(E_P = mgh)$ and kinetic energy $\left(E_K = \frac{1}{2}mv^2\right)$. These are macroscopic (big or bulk) forms of energy. But we have also been talking about the energy of the particles that make up the object. This is called its microscopic energy. The distinction between macroscopic and microscopic energy is important.

All objects contain particles such as atoms or molecules and it is the motion of these particles that makes up the microscopic energy of the object. This motion can be vibrational kinetic energy, as in solids, or rotational and translational kinetic energy, as in fluids (liquids and gases). The particles of matter also possess many forms of microscopic potential energy in the chemical bonds (covalent, ionic and metallic) that hold particles together. This is called **chemical energy**. There is also energy stored in the nucleus of the atoms. This is called **nuclear energy**.

macroscopic energy
big or bulk forms of energy not at an atomic scale

microscopic energy
energy of the particles that make up a substance including microscopic kinetic energy from the motion of particles and the microscopic potential energy of the chemical bonds and nucleus

chemical energy
microscopic potential energy contained in the bonds within and between particles

nuclear energy
microscopic potential energy contained within the nucleus of an atom

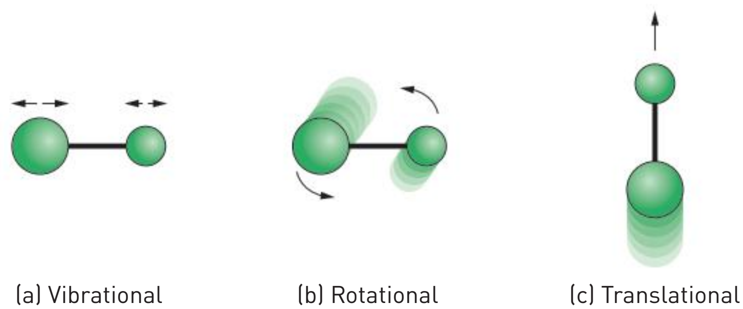

FIGURE 1 Three types of motion in molecules

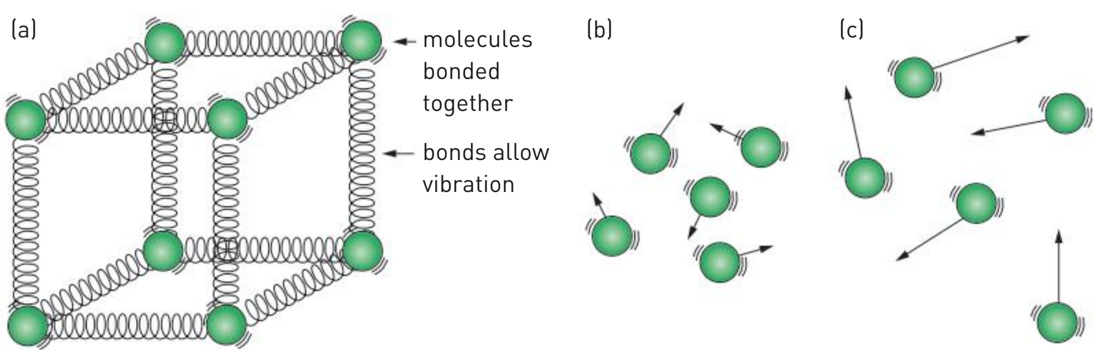

FIGURE 2 Main types of motion in each of the three states of matter: (a) vibrational motion in a solid; (b) translational motion in a liquid (plus some vibration and rotation); (c) translational motion in a gas (plus some vibration and rotation). There is also the chemical bond energy and nuclear energy inside the molecules.

Macroscopic energy

Consider a student throwing a ball (Figure 3). What energy does the ball possess?

You would say the ball has kinetic energy (KE or E_K) because of its motion from being thrown. This is equal to $\frac{1}{2}mv^2$, which means that as the object's velocity increases, its macroscopic kinetic energy increases. There is also gravitational potential energy (GPE or E_P) due to the ball's height above the ground ($E_P = mgh$). Macroscopic energy is defined as being due to the motion (velocity) or location (height) of an object in a gravitational, electromagnetic or electrostatic field.

Macroscopic energy is the sum of these two forms of energy:

$$E_{\text{macro}} = E_{K(\text{macro})} + E_{P(\text{macro})}$$

But is that all the energy the ball possesses?

FIGURE 3 The energy contained in a ball in flight due to its motion (E_K) and height (E_P), but note the gas molecules shown inside the ball.

Microscopic energy (internal energy)

Let's think about the situation if the motion of the gas particles inside the ball is considered. These particles could be the atoms, molecules, electrons or other particles that make up a substance. The total microscopic energy, E_{micro}, is made up of microscopic kinetic and microscopic potential energy.

$$E_{\text{micro}} = E_{K(\text{micro})} + E_{P(\text{micro})}$$

The $E_{K(\text{micro})}$ is made up of the microscopic kinetic energy due to translation, rotation and vibrations. The $E_{P(\text{micro})}$ is the microscopic potential energy of the bonds between particles in the substance, plus the binding of atoms by chemical bonds (E_{chem}). These bonds are broken and reformed during chemical reactions such as combustion. We have to also add in the microscopic nuclear energy (E_{nuclear}) contained inside the nucleus.

We can give this microscopic energy another name: **internal energy**.

Internal energy, U, is the total microscopic kinetic and microscopic potential energy of the particles in a system.

$$\text{Internal energy} = \text{microscopic kinetic energy} + \text{microscopic potential energy}$$

$$U = E_{K(\text{micro})} + E_{P(\text{micro})}$$

In thermal physics we are not concerned so much with the chemical and nuclear potential energy as they are not considered to change in the contexts we are dealing with. The energy in the chemical bonds and in the nucleus doesn't change for normal heating and cooling where no chemical reactions take place, so if we leave out these forms of energy we have **thermal energy**, E_{Th}. For senior physics we use the terms 'thermal energy' and 'internal energy' interchangeably. This is because we are not interested in the total internal energy or total thermal energy, only a change in them.

internal energy
the total (microscopic) potential energy and (microscopic) kinetic energy of the particles in a system

thermal energy
the internal energy present in a system due to its temperature. It does not include nuclear energy (symbol: U; unit: joule; unit symbol: J)

It is nearly impossible to sum up all the forces that contribute to internal energy. We can't measure internal energy directly, so instead we measure the change in internal energy because this is the same as the change in thermal energy. Because the nuclear and chemical bond energy doesn't change for normal heating and cooling, we can say:

Change in internal energy of a system equals the change in thermal energy

$$\Delta U = \Delta E_{th}$$

The *exact* split of internal or thermal energy into microscopic kinetic and microscopic potential energy is outside the scope of these chapters.

In summary, the total energy of the system (the ball) is the sum of the energy of the ball due to the macroscopic energy and microscopic energy:

$$E_{sys} = E_{macro} + E_{micro}$$
$$E_{sys} = E_{K(macro)} + E_{P(macro)} + E_{K(micro)} + E_{P(micro)}$$

TABLE 1 The forms of energy that make up total (or 'system') energy E_{sys}

	Macroscopic energy		Microscopic energy		
	E_K	E_P	E_K	E_P	E_P
Type	energy due to movement (KE)	gravity, electric fields, magnetic fields	vibrational, rotational, translational energy of particles	forces between the particles in the stretched bonds	chemical and nuclear bonds (E_{chem}) ($E_{nuclear}$)
System energy, E_{sys}	✓	✓	✓	✓	✓
Internal energy, U			✓	✓	✓
Thermal energy, E_{th}			✓	✓	
Changes during heating and cooling	stationary, and doesn't change		the split between these varies, and is uncertain		doesn't change

FIGURE 4 This netball has both kinetic energy from its motion and gravitational potential energy from its height above the ground.

You may wonder why internal energy was given the symbol U. In 1850, German physicist Rudolf Clausius was looking for a term to describe a previously undefined quantity related to the effect of heat on particles that was a function of velocity (v) and time (t). The letter 'U' was in between and it must have seemed logical. It doesn't stand for anything in real life.

Regarding thermal energy, we are not going to worry about macroscopic energy. We consider the objects to be stationary, and in stationary systems there is no change in macroscopic energy. That means the change in energy of the whole system is due purely to change in internal energy:

$$\Delta E_{sys} = \Delta U$$

Thermal energy is associated with temperature. That is, more thermal energy means a higher temperature, and vice versa.

Summary

- **Internal energy, U, is the total microscopic kinetic energy, $E_{K(micro)}$, and microscopic potential energy, $E_{P(micro)}$, of the particles in a system.** It does not include macroscopic energy.

$$U = E_{K(\text{micro})} + E_{P(\text{micro})}$$

- **Thermal energy, E_{th}, is the total kinetic and potential energy of the moving atoms and stretched bonds inside an object.** It does not include chemical or nuclear potential energy in the bonds.

$$E_{th} = E_{K(\text{micro})} + E_{P(\text{micro, excluding bond energy})}$$

- Thermal energy can also be regarded as that portion of internal energy that changes when the temperature of the system changes.
- Kinetic energy, E_K, is the energy associated with the motion of the particles in a system.

Study tip

It is important to be able to summarise and distinguish between internal energy, thermal energy and kinetic energy. The statements provided here are a good start.

CHECK YOUR LEARNING 1.3

Describe and explain

1. a **Identify** the name given to the internal energy of a substance.
   b **Describe** the form(s) of energy this involves.
2. **Explain** the difference between macroscopic and microscopic energy.
3. **Describe** the difference between thermal and internal energy.
4. **Explain** how heat, thermal energy and internal energy are related.

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- » Student book questions
  Check your learning 1.3
- » Weblink
  Temperature
- » Weblink
  Macroscopic energy
- » Weblink
  Microscopic energy

1.4

Kinetic energy and temperature

KEY IDEAS

In this section, you will learn about:

+ the relationship between kinetic energy and temperature
+ the nature of elastic collisions.

When you heat up a substance, the average kinetic energy of the particles increases (so long as there is no phase change). For instance, if you heat 100 mL and 200 mL of water in beakers on a hotplate, the particles get faster and faster and their kinetic energy increases. The larger volume needs more heat to make it reach 100°C and boil than the smaller volume does. But when the water in each beaker boils, the average kinetic energies of their molecules are the same. We can say:

temperature
a measurement of the warmth or coldness of an object or substance with reference to some standard value, e.g. the Celsius temperature scale

Temperature is a measure of the average kinetic energy of the particles in a system.

Heating and change in thermal energy

Recall that thermal energy is made up of kinetic and potential energy. So, if the kinetic energy of particles in a substance increases, so does its thermal energy (and, of course, its internal energy). Heating is the term used when some of the thermal energy is transferred from hot objects to cold objects, as in the case of a hot spoon being placed in cool water. We can thus define **heat as the transfer of thermal energy** in this heating process. A common misconception is that heat and temperature are the same, which is not the case. In common use it seems the same – you often hear 'turn up the heat' when referring to a room heater, when 'turn up the temperature' is meant. Heat is the *process* of transferring thermal energy in a system, whereas temperature is a *property* of the system.

A **change in temperature** is due to the addition or removal of energy from a system.

Let's consider the motion of particles in gases some more.

FIGURE 1 Perfume molecules evaporate and travel quickly as liquid droplets and then a gas. The hotter they are, the faster they travel.

A student at the back of the laboratory sprayed some deodorant in the air and within a few minutes it could be smelt out the front of the lab 8 metres away. Molecules of the perfume had travelled 8 metres in about a minute. Does that mean that molecules of perfume vapour (gas) must have a speed of 8 metres per minute? Not necessarily – they would have taken a zigzag path to get there or could have been transported in bulk by a breeze as well. The gas particles actually move at something like a few hundred metres per second, but they don't go far before colliding with each other and the air about them. They collide about 6000 times per second and travel a long, long distance to get to the front of the room. So, we can say that gas particles are moving. They can vibrate, rotate and go from one place to another. In other words, the gas particles have kinetic energy (Greek *kinema* = 'motion'). As you heat up a gas, the speed of the particles, and hence their kinetic energy, increases. This is shown by graph in Figure 2.

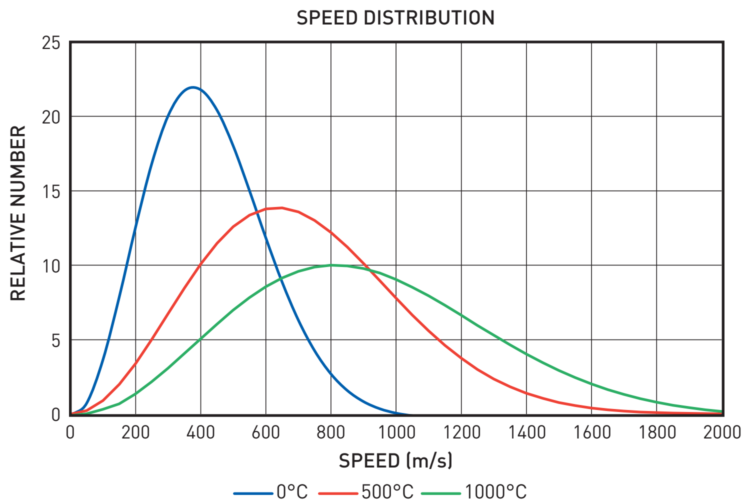

FIGURE 2 The speed of oxygen molecules at different temperatures. The most common speed is shown by the peak of each line. At 0°C (blue), the most common speed for oxygen is 400 m s^{-1}.

It would be impossible to measure the motion of all the particles within a substance because of the number of particles and the great variation in their speeds. Figure 2 indicates the variation of molecular speeds of oxygen gas, O_2, at various temperatures. However, at any one moment in time there will be some molecules that are moving faster and will have more kinetic energy, and some that are moving slower and have less kinetic energy. When these molecules collide, they do not lose energy but tend to swap it. If a fast and a slow molecule collide, they bounce off each other and the fast one becomes slow, and the slow one becomes fast.

As objects gain heat and become hotter, the particles move faster. At a temperature of 500°C, the most common speed for oxygen molecules is 650 m s^{-1} and at 1000°C it is 800 m s^{-1}.

CHALLENGE 1.4A

Air on your skin

Imagine a 1 cm square on your skin. Every second there are 10^{22} 'blows' from air molecules. Can you detect it? If you can't, state some reasons why you can't feel these blows. If the blows stopped, predict what you would feel.

Kinetic energy and temperature relationship

In the past you learnt that kinetic energy (E_K) relates to the mass and speed of an object. You learnt the formula $E_K = \frac{1}{2}mv^2$. That is, the kinetic energy is the product of the mass and velocity squared, all divided by two. For example, a 3 kg block moving at 10 m s^{-1} has a E_K of $\frac{1}{2} \times 3 \times 10^2 = 150$ joules (150 J). This is said to be the object's macroscopic kinetic energy. However, in this section we are concerned with the particles within the object, such as the microscopic gas particles inside a balloon. As the temperature rises, the average speed of gas molecules inside the balloon rises and thus the average kinetic energy of the gas rises.

We can say that **kinetic energy is directly related to the temperature of the system.** Kinetic energy of gas particles is shown by the formula:

$$E_K = \frac{3}{2}kT$$

E_K = average kinetic energy per molecule of gas (J)

k = Boltzmann's constant (1.38×10^{-23} J K^{-1})

T = temperature in kelvin (K). To convert from Celsius (°C), simply add 273 (you will see why later, but for now just do the conversion).

This formula implies that, at a given temperature, all gas molecules – no matter what their mass – have the same average kinetic energy. From Year 10 you know that E_K is also equal to $\frac{1}{2}mv^2$. We can put these two equations together to give:

$$E_K = \frac{3}{2}kT = \frac{1}{2}mv^2$$

WORKED EXAMPLE 1.4

Calculate the average kinetic energy of the air particles in a laboratory at 22°C.

SOLUTION

The average translational kinetic energy of a molecule of a gas can be found using the formula:

$$E_K = \frac{3}{2}kT$$

$$= \frac{3}{2} \times 1.38 \times 10^{-23} \times (22 + 273)$$

$$= 6.1 \times 10^{-21} \text{ J}$$

CHALLENGE 1.4B

Adiabatic compression

Space capsules get hot when they re-enter Earth's atmosphere. This is usually said to be because of the friction between the metal and the air, but this is wrong! Space capsules are heated as they plough into the atmosphere and compress the air ahead of them. Have you ever pumped up a bicycle tyre and discovered that the pump and the tyre have become hot? The same effect causes spacecraft and supersonic aircraft to heat up as they compress the air at their leading edges. It is called 'adiabatic compression'. Design an experiment to show that the reason the object becomes hot is not air friction.

Temperature and thermal energy

An electric kettle is quite a simple device. The longer you leave it turned on, the higher the temperature becomes (until it boils). That seems logical. A kettle is also quicker to heat up the less water there is in it. We could confidently say:

- the temperature increases as more thermal energy is added; or $\Delta T \propto$ thermal energy (Q)
- the temperature increase is greater with less mass of water; or $\Delta T \propto \frac{1}{\text{mass}}$.

  These could be combined to say $\Delta T \propto \frac{Q}{m}$, or:

$$Q = mc\Delta T$$

where c is a constant of proportionality known as 'specific heat capacity' (which we will look at more in the next chapter).

CHECK YOUR LEARNING 1.4

Describe and explain

1 **Explain** the meaning of temperature in terms of kinetic energy.

2 **Calculate** whether a nitrogen atom travelling at 400 m s^{-1} will take $\frac{1}{4}$ s to travel the 100 m from one end of the school oval to the other.

Apply, analyse and interpret

3 **Determine** at 1200°C, the average kinetic energies of:

a argon atoms

b nitrogen molecules.

4 **Deduce** the temperature of neon atoms given that the average E_K was found to be 1.2×10^{-20} J.

5 If you could suddenly increase the speed of every molecule in a gas by a factor of 2, **consider** if the temperature of the gas would increase by a factor of 2, $\sqrt{2}$ or 2^2.

Investigate, evaluate and communicate

6 **Propose** why nitrogen doesn't settle out near the ceiling and oxygen near the floor given that air is made up mostly of nitrogen and oxygen, and that nitrogen is lighter than oxygen.

7 **Evaluate** the claims that 'eating ice helps you lose weight' and that 'ice has negative joules' based on the idea that when you eat ice cubes, your body uses up energy to melt them and warm them up to body temperature.

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» Student book questions
Check your learning 1.4

» Challenge
1.4A Air on your skin

» Challenge
1.4B Adiabatic compression

» Weblink
Thermal energy

1.5 Measuring temperature

KEY IDEAS

In this section, you will learn about:

+ the Celsius, Fahrenheit and Kelvin scales as measures of temperature
+ how to convert between measurement scales.

In Section 1.4 you saw that temperature is defined as a measure of the average kinetic energy of the particles within a system. By 'system' we mean an isolated group of particles such as in a balloon, an ice block or a beaker of water. The relationship is stated as $E_K = \frac{3}{2}kT$ for gases. There is no need to memorise this formula, but the question remains: 'How do we measure temperature and what units are used?' People also ask, 'Why does Australia use Celsius for temperature, but the United States uses Fahrenheit?'

Measuring temperature requires the use of some property of a substance that changes proportionally with increase in temperature. Most temperature-measuring instruments use the property of expansion and contraction. In schools, the alcohol-in-glass thermometer is most common, whereas the mercury-in-glass is quite common in industry and research. Thermometers are calibrated to indicate the temperature. As temperature increases, the alcohol or mercury expands up a fine tube in the glass thermometer. The markings on the thermometer depend on the scale used (see Figure 1.)

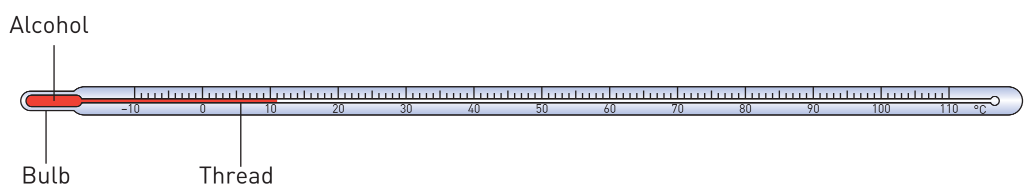

FIGURE 1 The liquid-in-glass thermometer. This one has alcohol, with a red dye, which expands more rapidly than the glass containing it. When the thermometer's temperature increases, the liquid from the bulb is forced into the narrow tube, producing a large change in the length of the column for a small change in temperature. Sometimes mercury is used as the liquid as it is suitable over a much larger range of temperatures (but dangerous if the thermometer is broken).

Throughout history, scientists have made up their own scales to measure temperature. Sir Isaac Newton made up a temperature scale where the freezing point of water was 0 degrees and normal body temperature was 12 degrees.

CHALLENGE 1.5

Cooling cannonballs

In 1780, French physicist Leclerc measured the rate of cooling of a very hot iron cannonball. Thermometers didn't exist, so he asked some women with soft hands to estimate the temperature. List three advantages and three disadvantages of this method.

Fahrenheit scale

A German physicist, Daniel Gabriel Fahrenheit (1686–1736), developed a liquid-in-glass thermometer and a temperature scale (now known as the **Fahrenheit scale**) that took the freezing point of an ice and salt mixture to be 0°F and his body temperature as 100°F. He marked those levels on his thermometer and divided the scale into 100 parts, one for each degree. The choices of his body temperature for 100°F and the freezing temperature of salt water for 0°F were unfortunate. Fahrenheit's metabolism was higher than most people, so 100°F for him resulted in 98.6°F as the body temperature for the average person.

Fahrenheit scale
a temperature scale that takes the temperature at which water freezes into ice as 32°F, and the boiling point of water as 212°F

Fahrenheit designated the freezing temperature of a brine solution made from equal parts of ice and salt as 0°F. But that is certainly not the coldest temperature you can experience in winter weather. It also makes the freezing point of pure water an awkward 32°F. Since ocean water is not saturated with salt, it freezes at 28°F. What a mess. No wonder most countries got rid of the Fahrenheit scale!

Although the Fahrenheit scale is no longer used in Australia, is still used in several other countries such as the United States, Burma, Liberia, Bahamas, Belize, Palau and the Cayman Islands. The Fahrenheit scale is now usually defined by two fixed points (as defined at sea level and standard atmospheric pressure): the temperature at which water freezes into ice is 32°F, and the boiling point of water is 212°F. These defined points give the scale a separation of 180°F.

The conversion between Fahrenheit and Celsius is:

$$T_C = (T_F - 32) \times \frac{5}{9}$$

Celsius scale

An easier decimal temperature scale was invented by a Swedish astronomer, Anders Celsius (1701–1744). On the **Celsius scale** (also called the centigrade scale), the freezing point of pure water is 0°C and the boiling point is 100°C. Interestingly, Celsius originally took the freezing point to be 100°C and boiling point to be 0°C, but this was changed in the first year. The Celsius scale is the main scale used in measuring body temperature and in all scientific work (see Figure 2). It is the common scale throughout most of the world.

Celsius scale
a temperature scale that takes absolute zero as −273.15°C and the triple point of water (where solid, liquid and gas exist together) as 0.01°C

Kelvin scale

The Fahrenheit and Celsius scales are relative scales – that is, zero degrees on either scale does not mean that this is the lowest temperature obtainable. Since temperature is a measure of the average kinetic energy of the particles, 0°C does not mean that all particle motion has stopped. So, at what temperature does all motion stop? This point would be the true limit of coldness and would produce an absolute zero temperature. William Thomson suggested this temperature was –273.15°C.

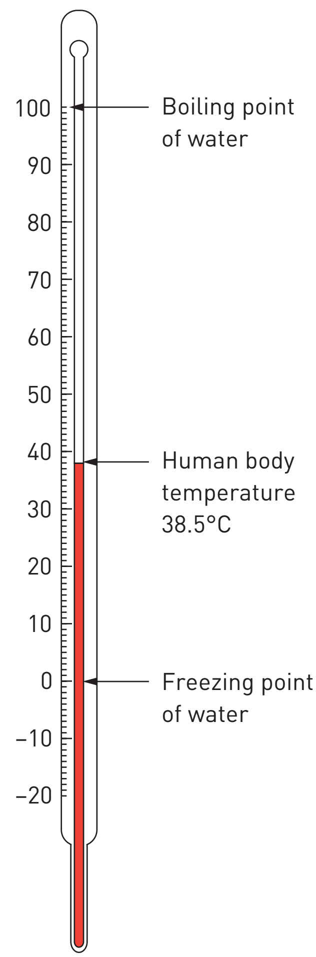

FIGURE 2 A Celsius thermometer is commonly used in the laboratory and in the home.

When a sample of gas of constant volume is heated, its pressure varies with its temperature in degrees Celsius. This is shown in Figure 3. Extrapolation of this graph suggests that, at –273.15°C, the pressure becomes zero and therefore all particle motion stops. This is because pressure is caused by particles colliding with the container walls – if there is no motion, there are no collisions and therefore no pressure. This point is called **absolute zero** on the **Kelvin scale** of temperature. However, one degree on the Kelvin scale is equal in magnitude to one degree on the Celsius scale.

absolute zero
the lowest temperature that is theoretically possible, at which the motion of particles which constitutes heat would be minimal. It is zero on the Kelvin scale

Kelvin scale
a temperature scale that takes absolute zero as 0 K and the triple point of water (where solid, liquid and gas exist together) as 273.15 K

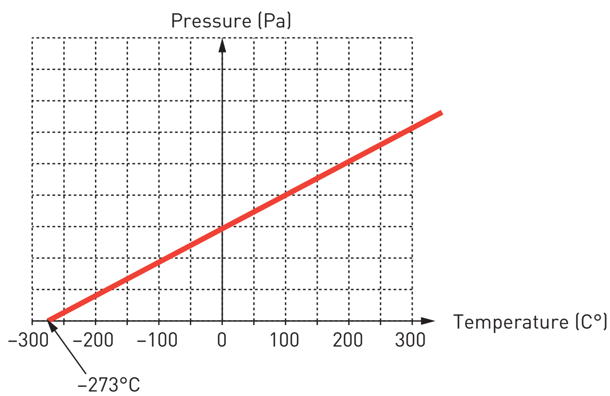

FIGURE 3 The relationship between temperature and pressure, and the establishment of absolute zero

Study tip

You might find it easier to remember the conversion from kelvin to Celsius as K = °C + 273.

At 0 K, the kinetic energy of the particles is zero and all that is left is microscopic potential energy. However, in terms of quantum mechanics (which is beyond what we need to know here), there is said to be some residual potential energy in the particles. This is called 'zero-point energy'. It is enough to say that, at 0 K, the system is in the lowest energy state rather than zero energy state.

Therefore, changing Celsius temperature to temperature in kelvins simply requires the addition of 273 (to three significant figures) to the Celsius value.

$$\text{kelvin temperature} = \text{Celsius temperature} + 273$$
$$T_K = T_C + 273$$

Figure 4 shows a comparison between the two scales.

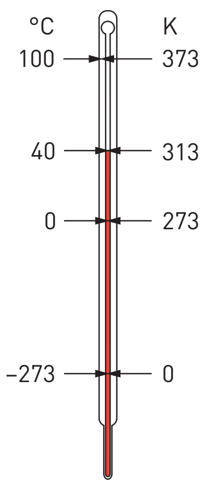

FIGURE 4 A comparison of temperature in degrees Celsius and kelvin

WORKED EXAMPLE 1.5A

Convert 50°C to kelvin.

SOLUTION

$T_K = T_C + 273$
$= 50°C + 273$
$= 323$ K

WORKED EXAMPLE 1.5B

Convert 486 K to °C.

SOLUTION

$T_K = T_C + 273$
$486 = T_C + 273$
$486 - 273 = T_C$
$T_C = 213°C$

Which scale is best?

The Kelvin and Celsius scales are defined using absolute zero (0 K) and the triple point of water (where solid, liquid and gas exist together, namely 273.15 K and 0.01°C) as their operational definition for the scale. However, it is impractical to use this definition at temperatures that are very different from the triple point of water. Accordingly, numerous defined points are now used, all of which are based on various thermodynamic equilibrium states of 14 pure chemical elements and one compound (water). Most of the defined points are based on a phase transition; specifically, the melting/freezing point of a pure chemical element. Other defining points are the triple point of hydrogen (–259.3467°C) and the freezing point of aluminium (660.323°C).

Fahrenheit, on the other hand, is also defined by the freezing and boiling points of water but not extended to other points. The other benefit of Fahrenheit is that a Fahrenheit degree is only $\frac{10}{17}$ the size of the Celsius degree, which allows more precise communication of measurements without resorting to fractional degrees.

In this Australian text, we will use °C and K.

TABLE 1 How to refer to each temperature scale correctly

Person's name	Daniel Gabriel **Fahrenheit**	Anders **Celsius**	Lord **Kelvin** (William Thomson)
Name of scale	the Fahrenheit scale	the Celsius scale	the Kelvin scale
Unit symbol	°F (e.g. 42°F)	°C (e.g. 18°C)	°K (e.g. 301 K)
Unit description	42 degrees Fahrenheit	18 degrees Celsius	301 kelvin (note the lowercase 'k')

CHECK YOUR LEARNING 1.5

Describe and explain

1 **Define** temperature.

2 **Identify** the lowest possible temperature on the Kelvin scale. Explain why is it called 'absolute zero'.

3 **Calculate** the following temperatures in K:
   a 20°C b –150°C c 520°C
   d –72°C e –300°C.

4 **Calculate** the following temperatures in °C:
   a 50 K b 278 K
   c 1000 K d –50 K.

5 **Identify** the scale an overseas friend was using if he said his son had a temperature of 99 degrees.

Apply, analyse and interpret

6 **Deduce** at what temperature °C and °F will be the same. **Explain** whether a kelvin temperature reading could ever be the same as a °C or °F reading.

Investigate, evaluate and communicate

7 **Propose** why the liquid in a thermometer rises as it heats up.

8 **Devise** a formula for converting Fahrenheit temperatures to kelvin to use when you go to the United States.

Check your obook assess for these additional resources and more:

» Student book questions
1.5 Check your learning

» Challenge
1.5 Cooling cannonballs

» Increase your knowledge
Precision and accuracy of alcohol in glass thermometers

» Weblink
Recording temperature

SCIENCE AS A HUMAN ENDEAVOUR

1.6 The development of temperature scales

KEY IDEAS

In this section, you will learn about:

+ the human endeavour behind the development of temperature scales.

For a large part of human history there has been no formal distinction between the concepts of heat and temperature. People spoke of the degrees of hot or cold, but these degrees were not measured – except perhaps in a very rough way as when a physician put their hand on a patient's forehead and diagnosed 'fever heat'. Leclerc asked young women to place their hands on cooling cannonballs to give him a sense of the degree of hotness.

Over the past 500 years there have been numerous temperature scales developed. Some of these are outlined in the timeline shown. However, the development of temperature measurement does not stop here (as you will see in the next section).

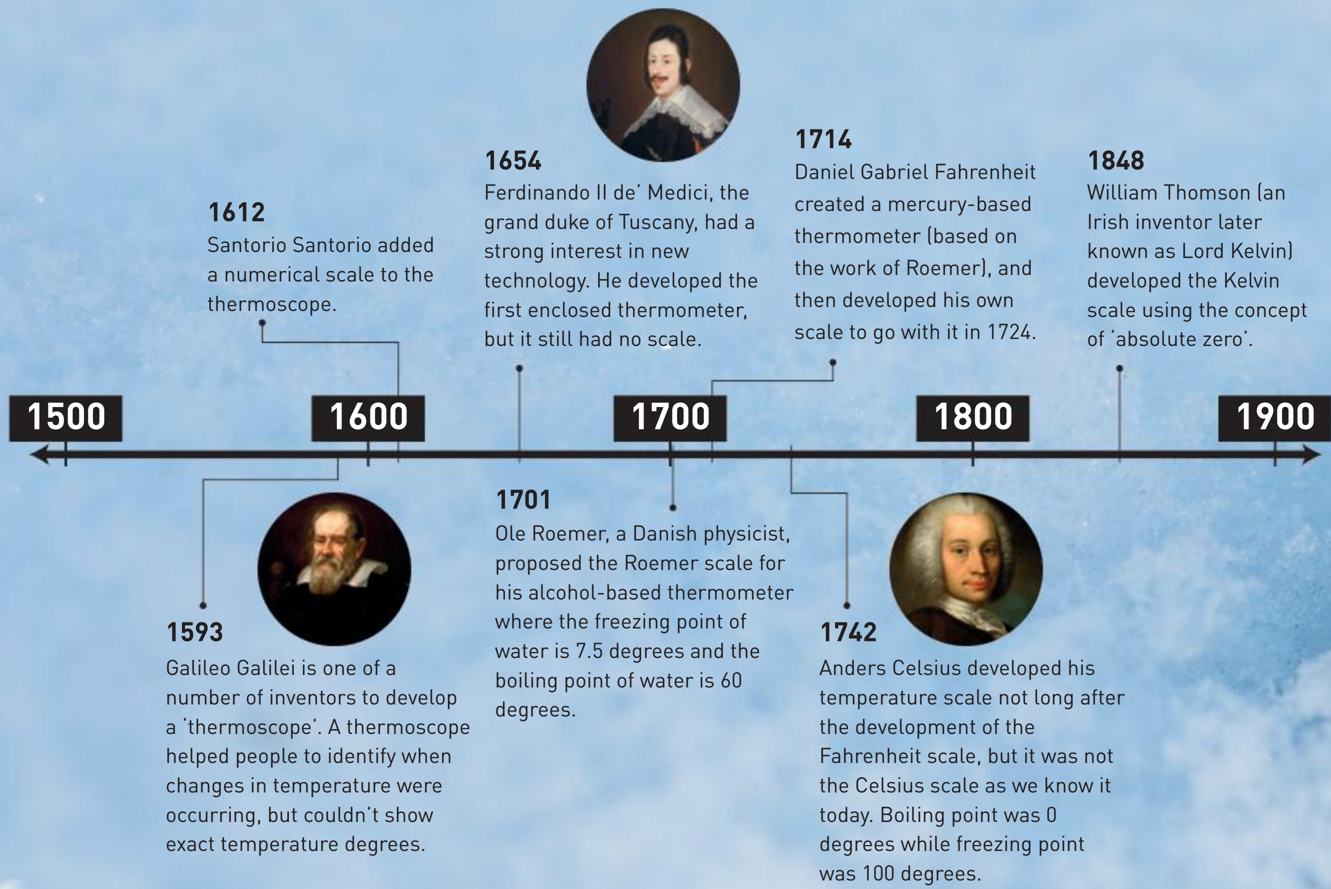

FIGURE 1 Timeline of the development of different temperature scales

There are two common definitions of temperature:

- Temperature is a measure of the average kinetic energy of the particles within a sample of matter.
- Temperature is the reading on a thermometer.

So, how does a thermometer register the kinetic energy of the particles? If the particles have zero E_K, then we can say the temperature is zero (kelvin). But what of other temperatures? The logic is simple. The theoretical basis for thermometers is the zeroth law of thermodynamics, which is illustrated as follows. Place a thermometer in substance A and when the substance and thermometer come to thermal equilibrium, take a reading. Then place the same thermometer in substance B and at equilibrium take a reading. If the reading is the same in both cases, then A and B are at the same temperature.

In simple terms, when two bodies have the same temperatures as a third body, then the two also have temperature equal to each other.

Thermometers tell us two things:

1. whether an object has the same temperature as another object (zeroth law)
2. the direction that thermal energy will flow spontaneously (from high temperature to low) when two objects of different temperatures are brought in contact (second law).

CHECK YOUR LEARNING 1.6

Describe and explain

1 **Explain** why the thermoscope would not have been a good way to measure temperature.

Apply, analyse and interpret

2 **Consider** the problem with temperature measurement before scales were invented.

Investigate, evaluate and communicate

3 **Evaluate** the comment: ‘The three common temperature scales – Fahrenheit, Celsius and Kelvin – were developed in the order stated. It is sometimes claimed that each was an improvement on the previous scale’.

a **Assess** this claim by analysing how and why these scales developed over time.

b **Discuss** the factors that prompted the review of temperature .

4 **Discuss** the problems associated with using the Fahrenheit scale given that the United States is one of the few countries in the world to still use it.

Check your obook assess for these additional resources and more:

- » **Student book questions** Check your learning 1.6
- » **Weblink** Celsius
- » **Weblink** Kelvin
- » **Weblink** Fahrenheit

1.7 Other types of thermometers

KEY IDEAS

In this section, you will learn about:

+ alternative methods of measuring temperature.

Even though liquid-in-glass thermometers are the most widely used, they have limitations. This is mainly due to the liquid freezing or boiling. Alcohol-in-glass thermometers can be used between –10°C and 110°C. Mercury-in-glass thermometers have an operating range of –40°C to 360°C. Glass is also fragile, and mercury is toxic to humans and other living beings. Liquids are also uneven in their expansion rate – it varies a tiny amount with temperature.

Gas thermometers

Gas thermometers rely on the expansion of gas. Since change in temperature is proportional to the change in volume of a gas, the expansion of a gas can be calibrated to measure temperature.

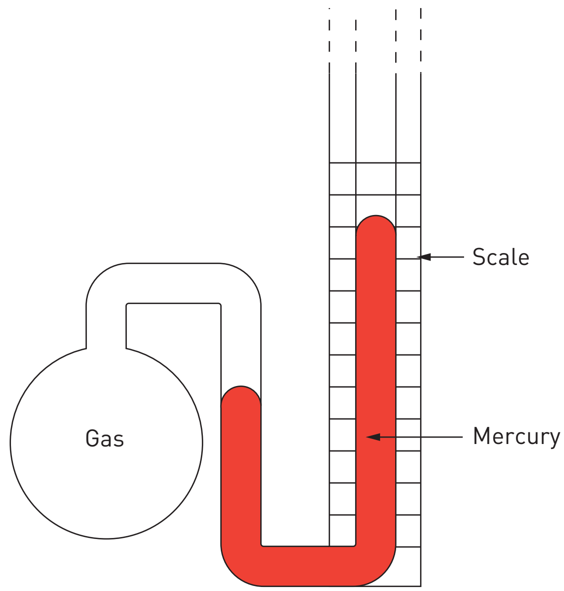

FIGURE 1 A constant volume gas thermometer relies on the relationship between temperature and pressure.

Resistance thermometers and thermocouples

Resistance thermometers, also known as resistance temperature detectors (RTDs), are sensors that utilise the properties of wires. Electric current in wires decreases as temperature rises, so the change in electric current of an RTD wire can be used to measure temperature. The RTD wire is a pure material that has an accurate resistance–temperature relationship (usually platinum, nickel or copper). As RTD components are very delicate, they often have a protective casing.

Thermocouples consist of two wires made of different metals. The wires are made into a loop that includes a voltmeter (see Figure 2). One end of the wire combination is kept at a reference temperature while the other end is used as a probe. When this probe is placed in a substance to be measured, the voltage produced is

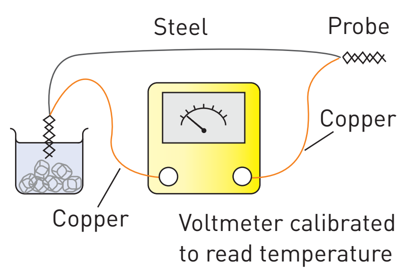

FIGURE 2 A thermocouple is a thermometer consisting of two dissimilar metals. The difference in the temperatures of the two ends produces a voltage. This can be calibrated to 'read' temperature.

proportional to the difference in temperature between the two ends. Thermocouples can be used to measure temperature over a wide range. For example, the nickel–chromium alloy and nickel–aluminium alloy combination has a range of –270°C to 1260°C. Even the much simpler copper and constantan (copper-nickel alloy) combination has a range of –270°C to 370°C.

Bimetallic strips

Bimetallic strips rely on the different expansion rates of two different metals. When heated, one metal expands more than the other. This causes bending and movement of a pointer across a scale. Bimetallic strips have a wide working range.

Liquid crystal thermometers

In **liquid crystal thermometers**, numbers on a scale are made of different crystalline chemicals. As temperature increases, these chemicals change their crystalline structure, which results in colour changes. Liquid crystal thermometers are not very accurate.

Pyrometers

Pyrometers measure the radiation given off by objects. The characteristic of the radiation changes with temperature. Infrared pyrometers can measure temperature from –20°C to 1500°C. Body temperature is routinely monitored in clinical settings with infrared ear thermometers, which measure the infrared energy emitted from the patient's eardrum in a calibrated length of time. A short tube with a protective sleeve is inserted into the ear, and a shutter is opened to allow radiation from the tympanic membrane to fall on an infrared detector for 0.1 to 0.3 seconds. The device beeps when data collection is completed, and a readout of temperature is produced on a liquid crystal display.

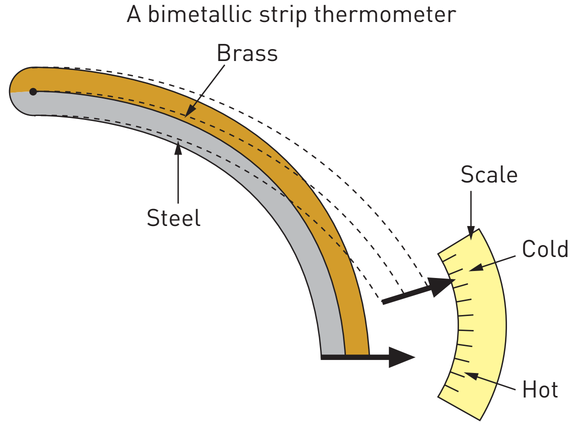

FIGURE 3 A bimetallic strip thermometer. The difference in expansion rates between the two different metals causes a pointer to move across a scale.

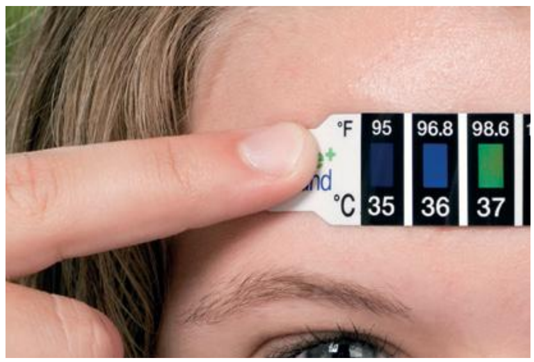

FIGURE 4 Liquid crystal thermometers are good for measuring body temperature. Each of the six squares on this plastic (liquid crystal) thermometer contains a film of a different heat-sensitive liquid crystal material. Below 35°C, all six squares are black. At 35°C, the first liquid crystal square changes colour. As the temperature rises, further crystals change colour.

FIGURE 5 An infrared pyrometer allows you to measure temperature without making physical contact. Normal skin temperature varies between 33°C and 37°C.

Thermistors

Thermistors are semiconductor devices that change their resistance with change in temperature. When these devices are heated, their resistance decreases and more current flows. The current is measured on an ammeter, which is calibrated to read temperature.

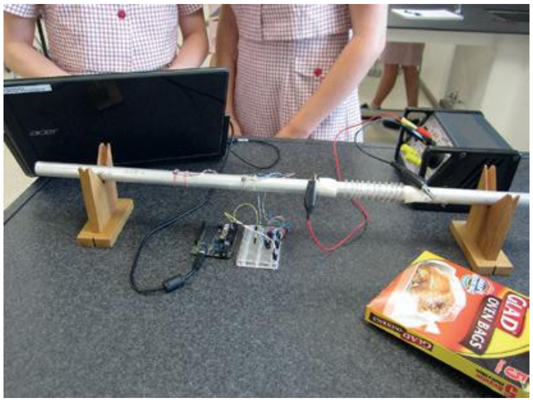

FIGURE 6 Three thermistors attached to a heated metal rod with rubber bands. Students were logging the temperature changes in the rod using an Arduino and thermistors. They could also have used a pyrometer (as in Figure 5).

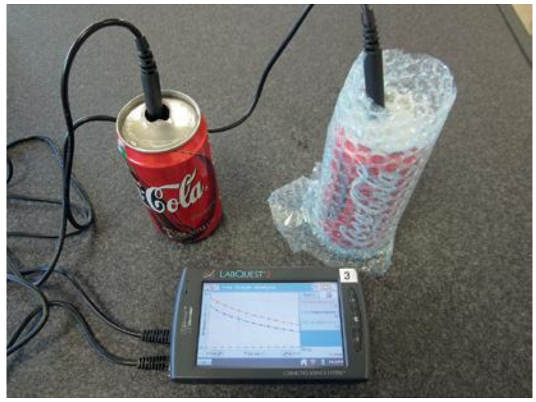

FIGURE 7 A stainless-steel temperature probe (as used in a science class) consists of a thermistor attached to a stainless-steel rod. It is being used here to measure the rate of cooling of water in an insulated can. Note the two graph lines on the screen.

CHECK YOUR LEARNING 1.7

Describe and explain

1 **Identify** and **describe** two methods of measuring heat that do not involve a liquid-in-glass thermometer.

2 **Summarise** why might someone choose to not use a liquid-in-glass thermometer.

Apply, analyse and interpret

3 Table 1 shows the effects of low body temperature. Death can be defined as a failure to revive on rewarming above 32°C. When people freeze to death in cold water, it has been reported that they do not seem to be in pain as they die. They often seem relaxed. **Deduce** why there might be an absence of pain.

TABLE 1 Effects of low body temperature

Body temperature (°C)	Effect
37.0 ± 1	normal
35	shivering
34	slurred speech
33	hallucinations
32	shivering stops
30	unconsciousness
26	appears dead

Check your obook assess for these additional resources and more:

» Student book questions
Check your learning 1.7

» Weblink
Thermometers

» Weblink
Thermometers and the environment

» Weblink
Thermometers and medicine

1.8 Thermal expansion

KEY IDEAS

In this section, you will learn about:

+ thermal expansion
+ expansion of gases, solids and liquids.

thermal expansion the tendency of matter to change in shape, area, and volume in response to a change in temperature

One of the consequences of heating a substance is that it expands. You saw this with the liquid in the stem of a thermometer. **Thermal expansion** is due to the increased speed of the particles, or the increased vibrations within and between the particles themselves.

This can easily be shown for each of the three common states of matter: solids, liquids and gases.

Expansion of gases

Consider a conical flask with a balloon over the opening. When heated, the increased speed of the gas molecules means they have a bigger impact on the walls of the flask. The flask is rigid, so it can't move when the molecules strike – the molecules just bounce off. However, the rubber balloon at the top of the flask can stretch. If we apply a force, the rubber will stretch and grow larger. The impact from the molecules on the rubber applies such a force, and will be greater than the force of the atmosphere pushing back, so the balloon moves outwards.

The effects of heat on gases are easy to understand because of the limited effect particles of the gas have on one another (except in collisions). The addition of thermal energy affects the particles of the gas by making them move faster, and thus expanding the gas or increasing its pressure on its container. Does heating have the same effect on the particles of liquids and solids?

Expansion of solids

Think about the following questions:

- Why do trains make the 'clickety–clack' sound when moving over railway lines?
- If you heat a steel ruler with a small hole in one end, does the hole get bigger or smaller?

With very few exceptions, all solids expand when they are heated and contract when they are cooled. What is the underlying cause of thermal expansion? Remember that an increase in temperature is a result of an increase in the kinetic energy of the individual atoms. In a solid, although the atoms or molecules are closely packed together (unlike in a gas), their kinetic energy (in the form of small, rapid vibrations) pushes neighbouring atoms or molecules apart from each other. This neighbour-to-neighbour pushing results in a slightly greater distance (on average) between neighbours, and adds up to a larger size for the whole body. For most substances under ordinary conditions there is no preferred direction, and an increase in temperature will increase the solid's size by a certain fraction in each dimension. In older train tracks, expansion gaps of about 10 mm had to be left for the steel rail to expand into. These gaps are responsible for the clickety clack noises of older trains.

The reverse of heating is cooling, and cooling causes contraction. For example, cooling a 15.000 m length of aluminium from 60°C to 20°C will cause it to contract by 9 mm.

Heat expansion may not seem very much, but if the length is big enough and the temperature rise large enough, the expansion will be noticeable. For example, in the early 1800s, steam had just been introduced to power the factories. Steam pipes in the cotton mills were often over 130 m long. With temperature rises from a cold 10°C to 400°C, the increase in length was such that a carpenter's ruler could be used to measure it.

FIGURE 1 Expansion gap left between the old railway lines

FIGURE 2 Thermal expansion joints, such as these in the Auckland Harbour Bridge in New Zealand, allow bridges to change length without buckling.

Volume expansion

A solid has three length measurements: length, width and height. All three directions expand or contract, therefore the volume of a solid changes with temperature change. This can be an advantage as well as a disadvantage in everyday life.

- Gear wheels are fitted to axles using cold shrinking. The axle is cooled in liquid nitrogen and it contracts, which allows the gear wheel to fit on easily. When the axle warms up to normal temperature, it makes a very tight fit. Cold shrinking has the advantage that it won't warp or discolour the metals, or change its crystal composition and hence its properties.
- Telephone and electrical cables are hung loosely between poles to allow for contraction in cold weather conditions.
- Bimetallic strips that consist of two dissimilar metals of equal length are used in fire alarms (see Figure 3).

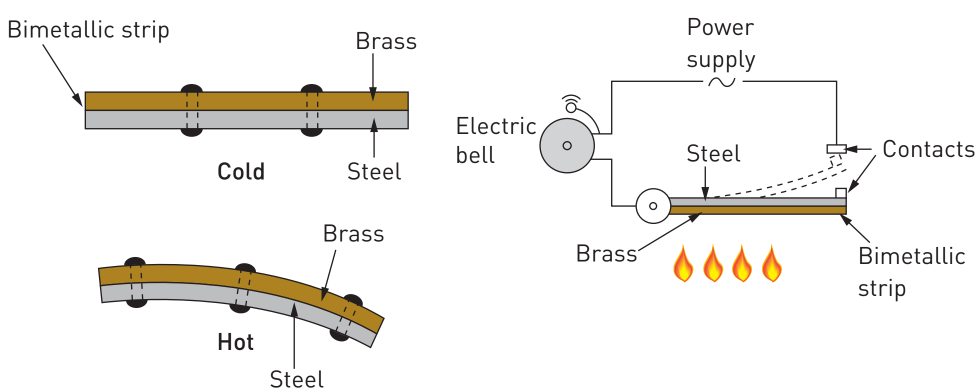

FIGURE 3 Bimetallic strip used in a fire alarm

- Bridges and rail lines have expansion gaps that allow for expansion in hot conditions to stop buckling.
- Large buildings and concrete paths often have rubber expansion gaps that allow for the expansion of the concrete, to stop cracking.
- Fillings in teeth and the teeth themselves need to have similar coefficients of expansion. A mismatch may result in microleakage and wear problems.
- Crown glass shatters when you pour boiling water into it, but pyrex does not.
- In aircraft manufacture, rivets are often cooled in dry ice before insertion and then allowed to expand to a tight fit.
- Pipes in refineries often include an expansion loop so that the pipe will not buckle as the temperature rises.

Expansion of liquids

A very common device making use of the expansion of liquids is a thermometer.

As the temperature increases, the mercury or alcohol in the thermometer increases in volume and moves up the fine tube. Another example of the expansion of liquids is the explosion of a bottle filled with liquid when it is left in the hot sunlight.

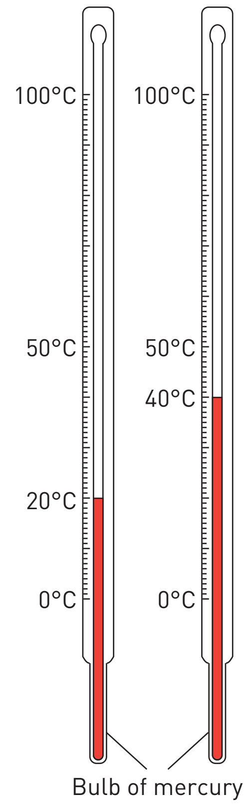

FIGURE 4 Expansion of mercury in a thermometer.

CHALLENGE 1.8

When should you buy petrol?

Differences in the thermal expansion of materials can lead to interesting effects at the service station. Are you better off buying petrol from the service station on a hot day or a cold day? You would think that on a hot day the petrol has expanded and there would be fewer molecules in a litre. What do you think?

CHECK YOUR LEARNING 1.8

Describe and explain

1 **Describe** the two essential properties of a liquid used in a thermometer.

Apply, analyse and interpret

2 **Consider** why houses with steel roofs on a timber frame will creak when a cloud passes overhead on a hot summer's day, Provide quantitative data to support your claim.

Check your obook assess for these additional resources and more:

» Student book questions
Check your learning 1.8

» Challenge
1.8 When should you buy petrol?

» Video
Thermal expansion of metals

» Video worksheet
Thermal expansion of metals

CHAPTER 1

Review

Summary

1.1
- Heat is energy in the process of being transferred from one place to another due to the temperature difference. It can be defined as the transfer of thermal energy.

1.2
- The kinetic particle model of matter suggests that matter is made up of particles that are constantly moving.
- States of matter include solids, liquids and gases.

1.3
- Objects can be considered to have their energy as two types: macroscopic energy and microscopic energy.
- Internal energy, *U*, is the total microscopic kinetic and microscopic potential energy of the particles in a system.
- Change in internal energy of a system equals the change in thermal energy.

1.4
- Temperature is a measure of the average kinetic energy of the particles in a system.
- Kinetic energy is directly related to the temperature of the system.

1.8
- Heating a substance causes it to expand due to the increased speed of the particles or the increased vibrations within and between the particles themselves.

Key terms

- absolute zero
- atom
- Celsius scale
- chemical energy
- energy
- Fahrenheit scale
- heat
- internal energy
- Kelvin scale
- kinetic energy
- macroscopic energy
- microscopic energy
- nuclear energy
- particle
- potential energy
- temperature
- thermal energy
- thermal expansion

Key formulas

Converting kelvin to degrees Celsius	Kelvin temperature = Celsius temperature + 273 $T_K = T_C + 273$

Revision questions

The relative difficulty of these questions is indicated by the number of stars beside each question number: ★ = low; ★★ = medium; ★★★ = high.

Multiple-choice

1 Which of the following statements about the kinetic theory of gases is NOT true:

A All molecules move with the same speed.

B Their average kinetic energy is directly proportional to the absolute temperature.

C All molecules make elastic collisions with each other and the walls of the container.

D The molecules travel in straight lines until they collide.

2 When one end of a cold metal spoon is placed upright in a cup of hot coffee, the other end gets hotter. Which one of the following best describes what is happening?

A Warmer molecules will rise to the top.

B The hot molecules produce thermal radiation that is then absorbed by the colder molecules.

C Higher-energy molecules hit lower-energy molecules, increasing their speed and therefore their temperature.

D Lower-energy molecules hit higher-energy molecules and the friction increases their temperature.

3 Three sealed flasks each containing 1 g of water, ice, and water vapour are at the same temperature. Which of the following is true about the internal energy of the substances?

A $U_{water} > U_{ice} > U_{vapour}$

B $U_{water} = U_{ice} = U_{vapour}$

C $U_{water} < U_{ice} < U_{vapour}$

D $U_{ice} < U_{water} < U_{vapour}$

4 A sealed container of air is kept at a constant temperature. What will happen to the speed of the molecules of air in the container as time passes?

A The molecules will all reach the same speed.

B Some molecules will speed up and others will slow down, but the average speed will be constant.

C The molecules will slow down.

D There will be no change.

5 A scientist is feeling sick and knows that if her temperature is a degree or more above 37.5°C she should go home from work. But all she has is a thermometer graduated in kelvin. What temperature does the thermometer need to show?

A 194.5 K B 310.5 K C 311.5 K

Short answer

Describe and explain

★ 6 **Define** temperature, energy and heat.

★ 7 **Describe** three differences between solids, liquids and gases.

★ 8 **Identify** the key phrase from each of the main points of the kinetic theory.

★ 9 You can compress gases easily but not solids. Can you partially compress liquids? **Explain**.

★ 10 **Describe** an elastic collision and explain how it pertains to gases.

★ 11 **Explain** why you can smell if a gas tap has been left on when you walk into a laboratory, but you cannot smell the water spilt on the front bench.

★ 12 **Explain** why it is good to have a common temperature scale around the world.

★ 13 **Describe** how allowances are made for the expansion of concrete paths, and explain why it works.

★ 14 **Calculate** the following Celsius temperatures in kelvin:

a 290°C b −25°C c 59.2°C

★ 15 **Calculate** the following temperatures in °C:

a 150 K b 378 K

c 6000 K d −10 K

★ 16 **Calculate** the following kelvin temperatures in °C:

a 69 K b 1376 K c 345.6 K

★★ 17 **Identify** the limitations of a model for gas behaviour that uses a box full of bees.

★★ 18 **Explain** the main assumptions we make about gases regarding their collisions.

★★ 19 A 1.00 cm cube of brass was weighed at 20°C and it was found to have a mass of 8.73 g. This gave a density of 8.73 g/cm^3. The cube was then heated to 120°C. The linear expansion value for brass is 19 μm per °C for every 1.0 m of length. **Calculate**:

a the new length of each side

b the new volume

c the density at 120 °C.

★★ **20** **Explain** which one of the graphs in Figure 1 best shows the relationship between kinetic energy of a gas molecule and its temperature (horizontal axis).

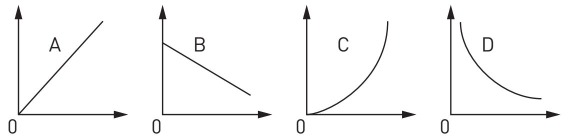

FIGURE 1

Apply, analyse and interpret

★ **21** **Determine** the following temperatures in K:

a 30°C b –120°C c 550°C

d –92°C e –200°C

★ **22** **Deduce** two reasons why a mercury-in-glass thermometer could not be used to measure the temperature of a pottery kiln when in use.

★ **23** **Compare** to decide which is better: a thermocouple or an alcohol-in-glass thermometer.

★ **24** **Compare** the thermal energy of a swimming pool at 30°C and a cup of coffee at 90°C.

★ **25** **Clarify** if heat and temperature are the same thing by giving an example of two objects that could contain the same heat (thermal) energy but at different temperatures.

★ **26** **Judge** the temperatures of the thermometers in Figure 2 to the nearest half-scale division.

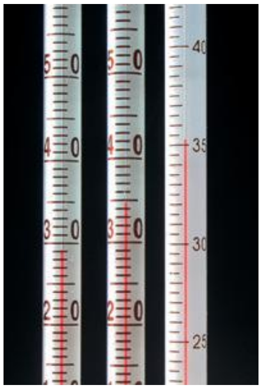

FIGURE 2

★ **27** **Consider** in terms of the particle model why metals expand when heated.

★ **28** **Consider** why some metals expand more than others – for instance, steel expands more than brass for the same temperature rise.

★ **29** **Deduce** whether the claim that 'liquids expand when heated, except for water, which shrinks' is true.

★ **30** Using kinetic theory, **consider** why, if you run hot water over a tight metal lid on a glass jar before trying to open it, it can be easier to open.

★ **31** **Consider** why some materials shrink with increasing temperature, given that liquids and solids expand with increasing temperature as the kinetic energy of the substance's atoms and molecules increases.

★★ **32** A 100.00 m long steel water pipe was laid in the ground on a day when the temperature was 25°C. A 1 m long rod of steel is known to change length by 10 micrometres for every 1°C change in temperature. **Determine** its new length if the ground temperature fell to –15°C.

★★ **33** The Statue of Liberty is made of a steel frame 46.00 m high. It experiences January temperatures as low as −5°C and once had a July summer temperature of 45°C. **Determine** the difference in height between the two extremes. You know that 1.0 m of steel expands by 10 μm per 1°C rise in temperature.

★★ **34** Suppose a metre ruler made of steel (of thermal expansion of 10×10^{-6} K^{-1}) and one made of invar (an alloy of iron and nickel with a coefficient of thermal expansion of 1.3×10^{-6} K^{-1}) are the same length at 0°C. **Determine** the difference in length between them at 22.0°C. (Steel has a coefficient of linear expansion of 10×10^{-6} K^{-1}).

★★ **35** **Determine** the fallacy in this claim: an advertisement for insulation said it would 'reduce roof temperatures from 60°C to 30°C, and that's a 50% reduction'.

★★★ **36** **Deduce** whether this statement is true or false: 'When you double the kelvin temperature of a gas, you double the average speed of the molecules.'

★★★ **37** There is a device inside many older lasers consisting of a ruby rod 30.00 cm long. The working temperature of the rod can get as high as 55°C.

a **Calculate** the increase in length for the 30.00 cm rod of ruby when it heats from

15°C to 55°C. A 1.00 m rod of ruby increases in length by 9.0 μm for each 1°C rise in temperature.

b **Determine** how many wavelengths of blue laser light this increase in length is equal to, given the wavelength of blue laser light is 473 nm. Note: nano (n) = 10^{-9}.

★★★ **38** Overhead power wires out on the street are made of aluminium and strung between poles 35.0 m apart. In mid-winter a particular wire contracted because of the cold and had no sag. In summer, when the temperature was really hot, the wire increased in length by 33.3 mm. **Determine** how much the centre of the wire sagged from the horizontal. Make whatever assumptions you need.

Investigate, evaluate and communicate

★ **39** **Explore** whether heating water from 20°C to 40°C really doubles the temperature.

★ **40** 'You can't see water molecules vibrate, but if you added food colouring you could.' **Assess** if this is true or false.

★ **41** **Evaluate** the statement that heat and cold flow like liquids because heat seems to 'run' from hot to cold.

★ **42** **Assess** whether you can say coldness flows from the ice to the water when you put an ice cube in water.

★ **43** To make a metal peg fit tightly in a hole in a metal block, the peg is made slightly larger than the hole. The peg is then cooled down and placed in the block. **Propose** a reason for this process. Why not just heat up the block instead?

★★ **44** **Devise** a graph, using a spreadsheet, showing the relationship between Kelvin and Celsius temperatures. Place degrees Celsius on the horizontal axis. Write the equation for the line in the form $y = mx + c$.

★★ **45** **Predict** what will happen when a trimetallic strip of metal, prepared using three metals, as shown in Figure 3, is heated. The coefficient of linear expansion value for brass is 19×10^{-6} K^{-1}, and for iron is 12×10^{-6} K^{-1}, and for copper is 17×10^{-6} K^{-1}, which means brass expands more than iron for the same temperature increase.

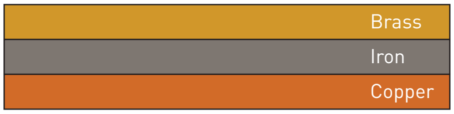

FIGURE 3

★★ **46** **Assess** the questions below based on the fact that water expands by about 10% when it freezes and produces sharp ice crystals.

a Why is it that a quarter of biological cells burst when animal or plant material is frozen?

b What are the implications of this cell damage in relation to preserving human bodies by freezing so that they can be thawed at some future date when it is hoped that all diseases are curable?

★★ **47** **Propose** what salt (NaCl) must do to the force of attraction between water molecules given that salty water heats up quicker than an equal mass of distilled water when the same amount of heat energy is added to both.

★★ **48** A 100.00 m long steel water pipe was laid in the ground on a day when the temperature was 25°C. **Determine** by what length it would have contracted if the ground temperature fell to –15°C.

★★ **49** You have two steel metre rulers: one made of carbon-steel and one made of nickel-steel. In the laboratory at 20°C they have exactly the same length of 1.000 m. They are both heated over Bunsen burners to 800°C. **Determine** how their lengths would compare if you could measure them without burning your fingers. A 1.0 m length of carbon-steel expands by 11 μm for each 1°C increase in temperature, whereas nickel-steel increases by just 1.3 μm.

Check your obook assess for these additional resources and more:

» Student book questions
Chapter 1 revision questions

» Revision notes
Chapter 1

» assess quiz
Auto-correcting multiple choice quiz

» Flashcard glossary
Chapter 1

CHAPTER 2

Specific heat capacity and calorimetry

Years ago, heat was once thought to be an invisible fluid, known as caloric. Bodies were capable of holding a certain amount of this fluid, hence the term heat capacity. Since the development of thermodynamics in the 1800s, scientists no longer consider heat to be a fluid, but rather a transfer of disordered energy. However, the term ‘heat capacity’ survives.

OBJECTIVES

- → Explain that a change in temperature is due to the addition or removal of energy from a system (without phase change).
- → Define specific heat capacity and the concept of proportionality.
- → Interpret tabulated and graphical data of heat added to a substance and its subsequent temperature change (without phase change).
- → Solve problems involving specific heat capacity.
- → Explain why the temperature of the system remains the same during the process of state change; explain it in terms of the internal energy of a system and the kinetic particle model of matter.
- → Define specific latent heat.
- → Solve problems involving specific latent heat.
- → Define thermal equilibrium in terms of temperature and the average kinetic energy of the particles in each of the systems.
- → Explain the process in which thermal energy is transferred between two systems until thermal equilibrium is achieved, and recognise this as the zeroth law of thermodynamics.
- → Solve problems involving specific heat capacity and specific latent heat, and thermal equilibrium.

Source: *Physics 2019 v1.2 General Senior Syllabus Queensland Curriculum & Assessment Authority*

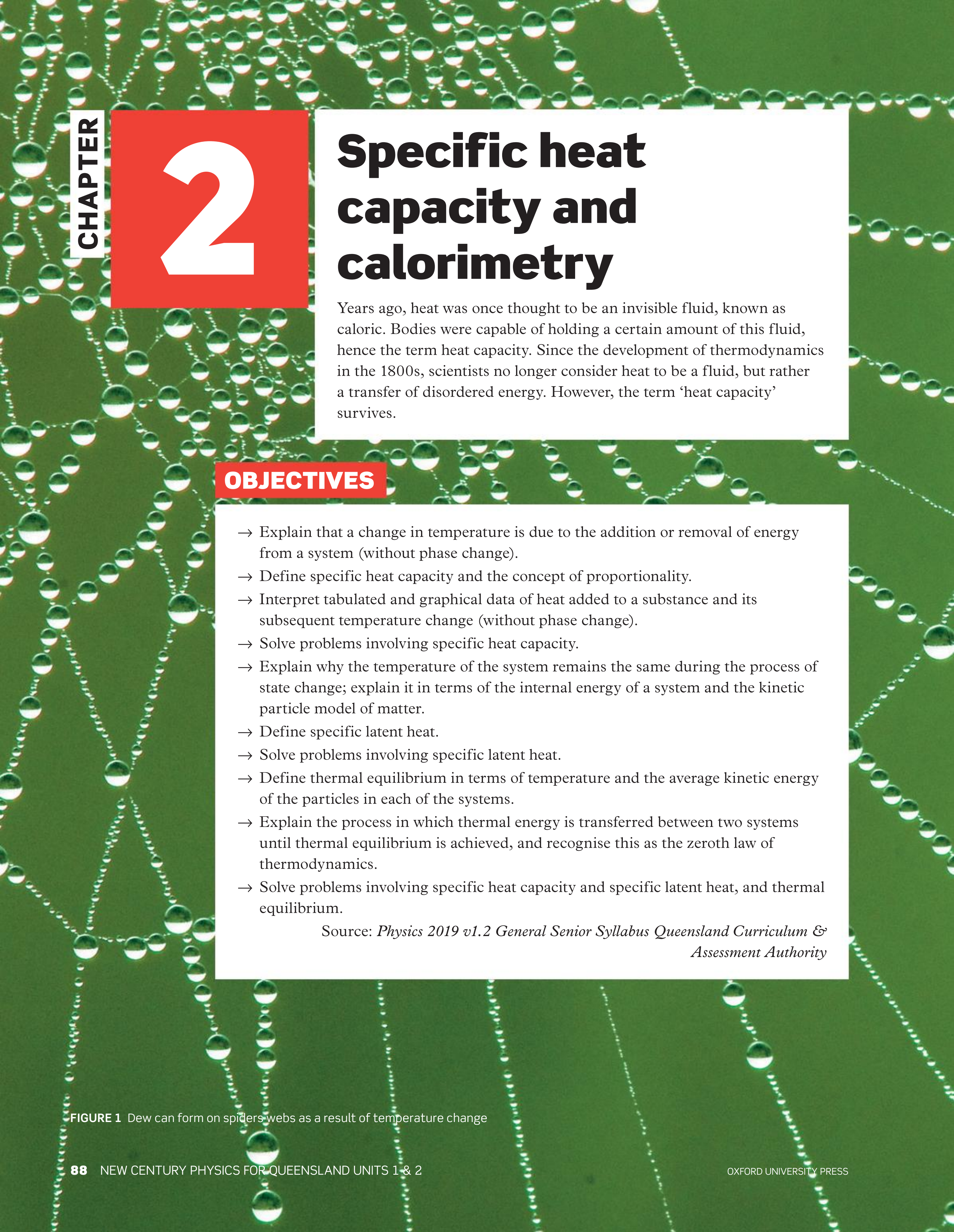

FIGURE 1 Dew can form on spiders webs as a result of temperature change

MAKES YOU WONDER

In this chapter we will be examining ideas that will help to answer questions such as:

→ Why do you feel colder when you are wearing wet clothes?

→ When you put an ice cube in water, can you say coldness flows from the ice to the water?

→ Why does steam burn you more than boiling water when they are both at 100°C?

→ The triple point for water is the temperature (0.01°C) and pressure at which water can exist in equilibrium in the liquid, solid (ice), and gaseous (water vapour) states. How can that be? Doesn't ice melt at 0°C and water boil at 100°C?

→ Can you have water at 100°C and steam at 100°C at the same time?

→ Evaporation and boiling are both processes for turning liquid into a gas. Are they the same thing or is there something different about them?

→ Is heating water from 20°C to 40°C really doubling the temperature?

PRACTICALS

MANDATORY PRACTICAL	**2.2** Specific heat of metal – by calorimetry
SUGGESTED PRACTICAL	**2.3** Calorimetry – method of mixtures
SUGGESTED PRACTICAL	**2.4** Observations of phase change – during heating

2.1 Thermal equilibrium

KEY IDEAS

In this section, you will learn about:

- thermal equilibrium
- the zeroth law of thermodynamics.

thermal equilibrium the situation when there is no net exchange of thermal energy between any components of a system, i.e. the components have the same temperature and the average kinetic energy of the particles is equal

zeroth law of thermodynamics if two bodies are in thermal equilibrium with a third body, they are in thermal equilibrium with each other

What happens when three metal blocks of different temperatures are placed in contact? Thermal energy transfers through the blocks until they reach **thermal equilibrium** (Greek *aequi* meaning 'equal', *libra* meaning 'balance').

Thermal equilibrium is the condition when two substances in physical contact with each other exchange no heat energy. Two substances in thermal equilibrium are said to be at the same temperature.

In Figure 1, the three blocks start at temperatures of 60°C, 50°C and 100°C (from left to right as shown), but soon all end up at 78°C. Note that the brass and aluminium are both in thermal equilibrium with the third block (iron), so we can say that brass and aluminium must be in thermal equilibrium with each other. We call this the **zeroth law of thermodynamics**.

Zeroth law of thermodynamics

The zeroth law of thermodynamics was first proposed by R. H. Fowler in 1931. It was called 'zeroth' because logically it should have preceded the first and second laws of thermodynamics, but was proposed after them.

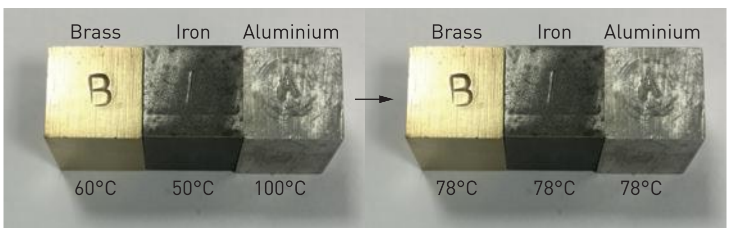

FIGURE 1 Three blocks reach thermal equilibrium

The zeroth law of thermodynamics states that if two bodies are in thermal equilibrium with a third body, they are in thermal equilibrium with each other.

This is the basis on which thermometers work. From the zeroth law we can say that two bodies (A and B) are in thermal equilibrium if they have the same temperature reading on a thermometer (C), even if A and B are not in contact with each other.

CHECK YOUR LEARNING 2.1

Describe and explain

1 **Describe** thermal equilibrium.

2 **Explain** the zeroth law of thermodynamics.

Check your obook assess for these additional resources and more:

» Student book questions
Check your learning 2.1

» Weblink
Temperature of metals

» Weblink
Thermal equilibrium

» Weblink
Laws of thermodynamics

2.2 Temperature and specific heat capacity

KEY IDEAS

In this section, you will learn about:

+ specific heat capacity and its formula.

FIGURE 1 Toasted cheese and tomato sandwich. Why does the tomato burn your mouth but not the bread? They are both at the same temperature.

Have you ever eaten a toasted cheese and tomato sandwich and noticed that the tomato is boiling hot and burns your mouth, but the cheese and the toast don't? Over 200 years ago, physicist Benjamin Thompson (Count Rumford) complained about the same thing with his hot apple pie. The liquid burnt his mouth, but the crust was okay to eat. It started him thinking that it points to something about the way different substances behave when they are heated up. This is the essence of thermodynamics.

Why do different substances heat up at different rates?

Identical beakers with the same volume of water heat at the same rate. But what if we changed the water for oil or a hydrocarbon such as petrol or cyclohexane – would they still heat up the same way? As you add thermal energy to a substance, it makes the molecules move faster and allows them to break away from one another and move around. If the bonds between molecules are strong, then it will take more thermal energy to achieve the same temperature rise (that is, the same increase in kinetic energy). Water molecules have hydrogen bonds between molecules and so water should resist temperature increase more than cyclohexane, which has no hydrogen bonds between molecules.

Specific heat capacity

Because of the great variation in molecular structure and bonds that exist between atoms in different substances, energy put into different substances does not result in the same temperature rises. For example, when walking along a beach on a hot day, the sand is a lot hotter than the grass or puddles of water. This is because sand only requires 880 J of thermal energy from the Sun to raise 1 kg by 1°C. Sea water requires 3900 J and fresh water requires 4180 J for 1 kg to rise by 1°C. This property is called the **specific heat capacity**, *c*, of the substance. Specific heat capacity is the amount of thermal energy transfer (heat) required to raise the temperature of 1 kg of a substance by 1°C.

specific heat capacity
the thermal energy required to raise the temperature of 1 kg of a substance by 1°C

TABLE 1 Specific heat capacity of some common substances

Substance	Specific heat capacity, c (J kg^{-1} K^{-1})
Gold	129
Lead	130
Mercury	140
Brass	380
Copper	390
Iron and steel	460
Glass	664
Sodium chloride	880
Sand	880
Aluminium	900
Wood	1700
Water (gas) – steam	2100
Water (solid) – ice*	2050
Acetone	2150
Paraffin	2200
Honey	2370
Alcohol	2450
Methylated spirits	2500
Water (liquid)	4180

*Note: the specific heat capacity of ice varies with temperature. It is only approximately 2100 J kg K^{-1}. At 0°C it is 2050 J kg^{-1} K^{-1}, and at −100°C it is just 1389 J kg^{-1} K^{-1}.

We could also say 'by 1 K' as a change of 1°C is equivalent to a change of 1 K. The term 'specific' means it is expressed in relation to a given amount of substance – in this case, 1 kg. Note that this only applies if there is no melting or vaporisation (no phase change) involved. Heating water from 98°C to 99°C is very different from heating it from 99.5°C to 100.5°C, as a phase change will then have occurred. You will see later that phase changes require energy, although there will be no temperature change. The specific heat capacity of some common substances is given in Table 1.

Why do ice and liquid water have different specific heat capacities?

When ice is heated, the kinetic energy of its molecules increases. Ice just has one mode of movement – vibration. So as ice heats up, the vibrations increase. However, as liquid water is heated, the molecules can use the added energy to increase their vibration as well as rotation and translation. Liquid water has more modes of movement to use up added heat energy than ice does. Hence, ice rises in temperature faster than water for the same amount of added energy. That is, it takes on average 2050 J to raise the temperature of 1 kg of ice by 1°C, whereas it takes 4180 J to warm the same amount of liquid water by the same amount (1°C).

Specific heat capacity formula

The equation to determine the specific heat capacity of a substance is: $Q = mc\Delta T$, where Q is the change in thermal energy (in J), m is the mass of the object (in kg), c is the specific heat capacity (in J kg^{-1} K^{-1}), and ΔT is the change in temperature. You must express ΔT as $T_{final} - T_{initial}$. We use Q as the symbol for 'quantity' of thermal energy.

Study tip

If ΔT is negative, then this is the quantity of thermal energy given off by an object.
If you also study chemistry, you may find the unit of grams is preferred and the specific heat capacity is divided by 1000. For example, the specific heat capacity of water can be written as 4200 J kg^{-1} K^{-1} or 4.2 J g^{-1} K^{-1}.

Study tip

More worked examples can be found on your obook assess.

WORKED EXAMPLE 2.2A

How much thermal energy is required to heat the following items from 30°C to 120°C?

a 2.0 kg steel barbeque plate

b \$2 coin of mass 6.6 g (specific heat capacity = 380 J kg^{-1} K^{-1})

SOLUTION

a $Q = mc\Delta T$

$= 2.0 \times 460 \times (120 - 30)$

$= 82\,800$ J

$= 83\,000$ J (2 sf)

b $Q = mc\Delta T$

$= \frac{6.6}{1000} \times 380 \times (120 - 30)$

$= 226$ J

$= 230$ J (2 sf)

(Note: to convert g to kg, divide by 1000.)

WORKED EXAMPLE 2.2B

How much heat energy is required to bring a saucepan containing 500 mL of water at 20°C to boiling point? (1 L of water has a mass of 1 kg.)

SOLUTION

$Q = mc\Delta T$

$= 0.500 \times 4180 \times (100 - 20)$

$= 1.67 \times 10^5$ J

$= 1.7 \times 10^5$ J (2 sf)

MANDATORY PRACTICAL

2.2 Specific heat of a metal – by calorimetry
Go to page 478 »

CHALLENGE 2.2

Testing oil temperature

For a demonstration to introduce specific heat capacity to a Year 11 physics class, equal masses of water and oil were added to separate beakers and placed on a hotplate. After 2 minutes, the water temperature was measured as 60°C. Would the oil be at a higher or lower temperature?

CHECK YOUR LEARNING 2.2

Describe and explain

1 **Calculate** the thermal energy, *Q*, absorbed when 1.5 kg of paraffin is raised from 15°C to 50°C.

Apply, analyse and interpret

2 **Determine** how much thermal energy could be absorbed by a 3.0 kg block of ice at –10°C before it reaches its melting point.

3 A liquid is heated in a beaker. If it takes 7500 J of thermal energy to increase the temperature of 500 g of the liquid by 6.0°C, **determine** what the liquid could be.

4 Table 2 shows the variation in specific heat capacity of ice with temperature.

a **Determine** if there is a relationship between the variables.

b **Deduce** why the specific heat capacity of ice is lower than for liquid water.

Table 2

Temperature (K)	173	193	213	233	253	273
Specific heat capacity (J kg^{-1} K^{-1})	1389	1536	1681	1818	1943	2050

5 Students were testing the ability of shade cloth to shield water from the Sun's heat. They took five metal cans, placed 10.0 mL of tap water in each, and wrapped them in different types of shade cloth ranging from 10% transmission (which lets 10% of the rays through) to 90% transmission. The students put the cans in direct sunlight and measured the temperature change after 1 hour. The results are shown in Figure 2.

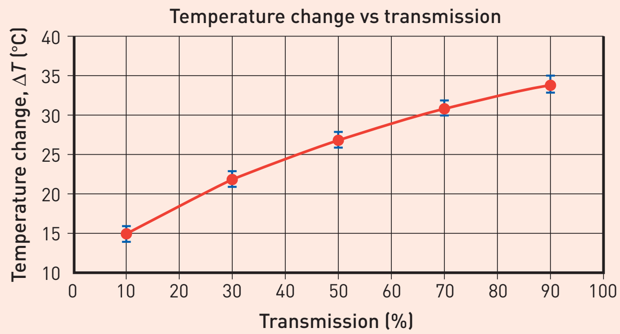

FIGURE 2 Temperature change of cans

a **Explain** if the relationship between ΔT and % transmission is linear.

b Students hypothesised that the relationship was $\Delta T = k \times \sqrt{(\% \text{ transmission})} + c$, so they plotted the graph shown in Figure 3. **Consider** whether this graph confirms their suggestion.

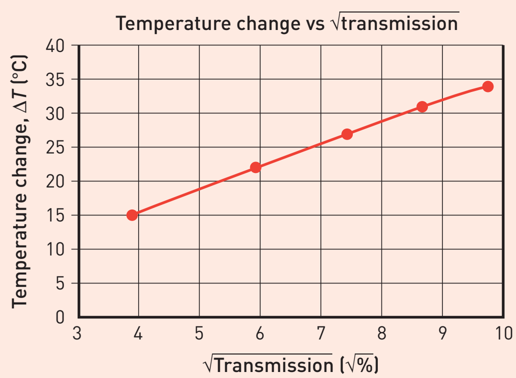

FIGURE 3 Relationship between $\Delta T = k \times \sqrt{(\% \text{ transmission})} + c$ % transmission and temperature change

Check your obook assess for these additional resources and more:

» Student book questions
Check your learning 2.2

» Mandatory practical
2.2 Specific heat of a metal by calorimetry

» Challenge
2.2 Testing oil temperature

» Increase your knowledge
Worked examples

2.3 Calorimetry

KEY IDEAS

In this section, you will learn about:

+ calorimetry.

calorimetry the science of measuring the amount of heat transferred between objects or in a chemical reaction

One process that makes use of energy conservation ideas is **calorimetry**. The word comes from Latin *calor* meaning 'heat', but originally from the Sanskrit *carad* meaning 'harvest' (which is literally 'hot time'). The *metry* means 'to measure', so calorimetry is about measuring heat.

Thermal energy transfer

Solid + solid

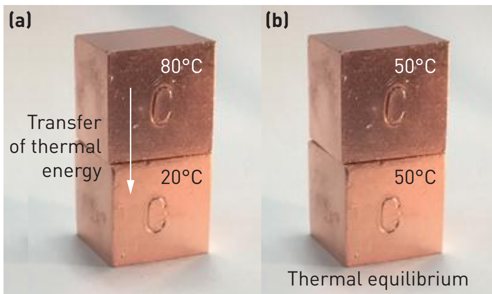

FIGURE 1 (a) Two small cubes of copper at different temperatures are placed in contact. (b) There is a transfer of thermal energy (heat), from hot to cold, until thermal equilibrium is reached (b).

The simplest case of thermal energy transfer involves two metals in contact with each other.

If two substances of different temperatures are placed in contact, they gradually come to the same temperature. The thermal energy transferred ('lost') out of the hot object in the exchange is equal in size to the thermal energy 'gained' by the other. We are assuming this is a closed system – one where no energy can escape to the surroundings. In simple words, the heat lost equals the heat gained.

However, it is better to state this in terms of the **conservation of energy**. There is no change to the total thermal energy of the system – it has just been redistributed. The sum of heat energy lost and heat energy gained equals zero (0) – they cancel out. Once they reach the (same) final temperature, they are said to be in thermal equilibrium. There is an equal balance of average kinetic energies so that no thermal energy transfers between the two blocks in the system.

conservation of energy the total energy of an isolated system remains constant

For systems in thermal equilibrium:

- no heat flows between the objects
- the average kinetic energy of the particles is the same.

Therefore:

- the respective temperatures of the objects are also the same.

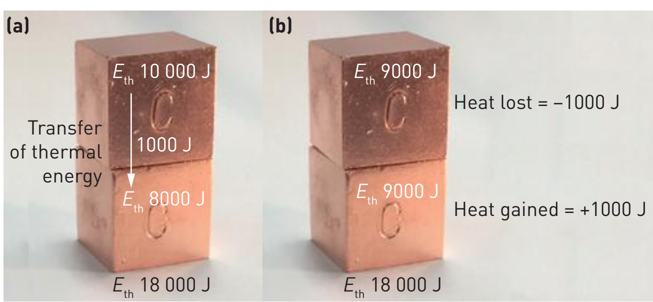

FIGURE 2 The total thermal energy of the system remains the same at 18 000 J. The heat lost (–1000 J) plus the heat gained (+1000 J) adds to zero. That is, the net energy difference is zero.

Let's revisit the two copper blocks in contact. Imagine the hotter block has a total thermal energy of 10 000 J and the cooler block has a thermal energy of 8000 J (see Figure 2). If 1000 J is transferred from the hot block to the cold block, then they finish up with 9000 J each. The hot block has lost 1000 J (–1000 J), and the cool block has gained 1000 J (+1000 J). The net change in thermal energy is (–1000 J) + (+1000 J) = 0 J. Energy is conserved – it is the same as it was at the start.

Mathematically, for systems coming to thermal equilibrium, we can state this relationship:

Heat lost by one substance + heat gained by the other substance = 0

$Q_{lost} + Q_{gained} = 0$

$Q_L + Q_G = 0$

$-Q_L = Q_G$

using the relationship $Q = mc\Delta T$, $-mc\Delta T$ (lost from the hot block) = $mc\Delta T$ (gained by the cold block) $-\left(m_{\text{hot block}} c_{\text{copper}}\left(T_f - T_i\right)\right) = m_{\text{cold block}} c_{\text{copper}}\left(T_f - T_i\right)$

Note that temperature change, ΔT, is always written as $T_f - T_i$. For the 'heat lost' side of the equation, this would give a negative number for $T_f - T_i$ as the initial temperature is always greater than the final temperature for the substance losing heat. The 'heat gained' side remains positive for ΔT.

This principle is an extension of the **law of conservation of energy – energy is not lost or gained, just transferred or transformed**. In thermodynamics, it is called the **first law of thermodynamics**.

first law of thermodynamics during an interaction between a system and its surroundings, the amount of energy gained by the system must be exactly equal to the amount of energy lost by the surroundings

In practice, there is always some heat lost unless insulation is ideal. However, heat losses to the surroundings can be minimised if experiments are carried out quickly.

WORKED EXAMPLE 2.3A

A 70.0 g copper block at a temperature of 80.0°C is placed in contact with another copper block of the same mass at a temperature of 20.0°C. Calculate the final temperature when the blocks have reached thermal equilibrium.

SOLUTION

$$-Q_L = Q_G$$

$$-m_{\text{hot copper}} c_{\text{copper}}(T_f - T_i) = m_{\text{cold copper}} c_{\text{copper}}(T_f - T_i)$$

$$-(0.070 \times 390 \times (T_f - 80.0)) = 0.070 \times 390\ (T_f - 20.0)$$

$$-(27.3\,T_f - 2184) = 27.3\,T_f - 546$$

$$-27.3\,T_f + 2184 = 27.3\,T_f - 546$$

$$54.6\,T_f = 2730$$

$$T_f = 50°\text{C}$$

Note: if your answer is 30°C, check that you have the +/− signs correct.

WORKED EXAMPLE 2.3B

50 mL (0.050 kg) of hot water at 80°C is mixed with 150 mL of cold water at 5°C. Calculate the final temperature when thermal equilibrium is reached.

SOLUTION

$$-Q_L = Q_G$$

$$-m_{\text{hot water}} c_{\text{water}}(T_f - T_i) = m_{\text{cold water}} c_{\text{water}}(T_f - T_i)$$

$$-(0.050 \times 4180 \times (T_f - 80)) = 0.150 \times 4180\ (T_f - 5)$$

$$-209\,T_f + 16\,720 = 627\,T_f - 3135$$

$$-836\,T_f = -19\,855$$

$$T_f = 23.8°\text{C}$$

$$= 24°\text{C (2 sf)}$$

Study tip

You will need to conduct an extended 'student experiment' as part of your physics course. A good one to consider is the specific heat capacity of a metal by 'coffee cup calorimetry'.

Study tip

Information about calorimeters can be found on your obook assess.

WORKED EXAMPLE 2.3C

If 100 g of alcohol (ethanol) at 50°C is mixed with 250 g of water at 20°C, what is the final temperature of the mixture?

SOLUTION

$$-Q_L(\text{alcohol}) = Q_G(\text{water})$$
$$-(mc\Delta T)_{\text{alcohol}} = (mc\Delta T)_{\text{water}}$$
$$-(0.1 \times 2450 \times (T_f - 50)) = 0.250 \times 4180 \times (T_f - 20)$$
$$-(245\,T_f - 12\,250) = 1045\,T_f - 20\,900$$
$$-245\,T_f + 12\,250 = 1045\,T_f - 20\,900$$
$$-1290\,T_f = -33\,150$$
$$T_f = 25.7°\text{C}$$
$$= 26°\text{C (2 sf)}$$

Liquid + liquid

In the previous section you saw that there is thermal energy transfer between two solids in contact until they come to thermal equilibrium. The same is true of two liquids, although thermal equilibrium is reached much faster.

Liquid + solid

Another type of calorimetry experiment is adding a hot solid to cool water to measure the solid's specific heat capacity. This makes a great little experiment in physics class.

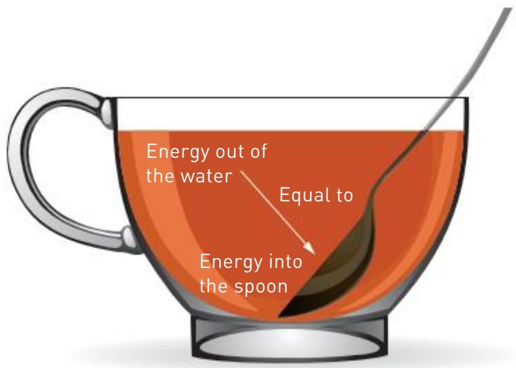

FIGURE 3 The amount of thermal energy transferred out of the hot water equals the thermal energy transferred into the spoon. Both eventually reach an equilibrium temperature somewhere in between both temperatures.

WORKED EXAMPLE 2.3D

A 20 g stainless steel spoon at room temperature (20°C) is placed in 200 mL of coffee at 70°C in a foam cup. Assume the foam cup doesn't absorb any energy. Calculate the temperature when thermal equilibrium is established. The specific heat capacity of stainless steel is 500 J kg^{-1} K^{-1}.

SOLUTION

$$-Q_L = Q_G$$
$$-m_{\text{water}}c_{\text{water}}\left(T_f - T_i\right) = m_{\text{spoon}}c_{\text{spoon}}\left(T_f - T_i\right)$$
$$-0.200 \times 4180 \times (T_f - 70) = 0.020 \times 500 \times (T_f - 20)$$
$$-836\,T_f + 58\,520 = 10\,T_f - 200$$
$$-846\,T_f = -58\,720$$
$$T_f = 69.4°\text{C}$$
$$= 69°\text{C (2 sf)}$$

CHALLENGE 2.3

Adding volume not temperature

A common mistake among lower primary students is to say that when two identical glasses of water, both at 40°C, are mixed, the final temperature will be 80°C. Write an explanation suitable for a Year 3 student about why this is not true. Next, explain why you add the volumes together (1 cup + 1 cup = 2 cups) but you don't add the temperatures together.

FIGURE 4 Determining thermal equilibrium between two liquids

CHECK YOUR LEARNING 2.3

Describe and explain

1 **Explain** what calorimetry is.

2 **Describe** what happens when two substances at different temperatures come into contact.

Apply, analyse and interpret

3 200 g of water at 80.0°C is mixed with 100 g of gold at 20.0°C.

a **Determine** the specific heat capacity of gold if the final temperature is 79.0°C.

b **Determine** the absolute error and percentage error in the rest, given the accepted value is 129.0 J kg^{-1} K^{-1}.

4 100 g of water initially at 30°C is mixed with 350 g of lead (c_{Pb} = 130 J kg^{-1} K^{-1}) resulting in a final temperature of 15°C. **Determine** the initial temperature of the lead.

5 250 g of water at 80°C is mixed with 1000 g of aluminium at 20°C and 500 g of zinc (c_{Zn} = 388 J kg^{-1} K^{-1}) also at 20°C. **Determine** the final temperature of the mixture.

6 In an experiment to determine the specific heat capacity of acetone, a copper calorimeter was used (as a foam cup would be dissolved by the acetone). In this experiment, 100.0 g of water was placed in a copper calorimeter (c_{Cu} = 390 J kg^{-1} °C^{-1}) of mass 150.0 g and the temperature was measured as 40.0°C. Chilled acetone of mass 145.0 g and temperature 15.0°C was added to the water, and the lid was placed on. A final temperature of 30.0°C was found at equilibrium.

a **Determine** the specific heat capacity of acetone.

b **Determine** the relative error, given the accepted value is 2150 J kg^{-1} °C^{-1}.

Check your obook assess for these additional resources and more:

- » **Student book questions**
  Check your learning 2.3
- » **Suggested practical**
  2.3 Calorimetry – method of mixtures
- » **Challenge**
  2.3 Adding volume not temperature
- » **Increase your knowledge**
  Calorimeters

2.4 Changes of state and specific latent heat

KEY IDEAS

In this section, you will learn about:

- changing states of matter including melting, vaporisation, evaporation, condensation and freezing
- specific latent heat.

FIGURE 1 This snowman was made in fresh snow. The sun is shining – why doesn't the snowman melt? Will a coat make the snowman melt faster or slower?

Phase change

When you eat an icy pole, the ice melts in your mouth and turns from frozen water into liquid water – but it is still water molecules (H_2O). Instead of being lumped together in a solid form, the molecules are now free to move. When you heat up water in a kettle, the liquid water turns into steam – it is still H_2O molecules, but they are now free to move around even more. These are the three phases of water: solid, liquid, gas. When water is changed from one to another by the addition or removal of thermal energy, we say it has undergone a 'change of state' or 'change of phase'.

Up until now we have only considered substances changing their temperature as heat is added or taken away, but not melting or boiling. We will now look at what happens when substances change state – when they change from a solid to a liquid or from a liquid to a gas (and vice versa).

FIGURE 2 Water turns into steam when enough thermal energy is added.

FIGURE 3 When we eat icy poles, how come the moisture in our mouth doesn't freeze?

Melting – from solid to liquid

If you have a beaker containing ice at –10°C and heat it, the temperature rises but the ice remains frozen solid. With continued heating, you would notice that when the thermometer approached 0°C, the ice started to melt around the base and you could swirl the ice around in the beaker with the thermometer. But even as heat energy was transferred from the hotplate, the temperature stayed at 0°C; you just got more and more liquid water.

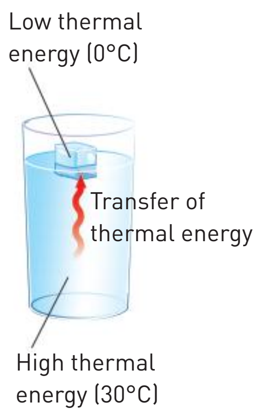

FIGURE 4 Energy transfers in melting ice

The **melting** of ice to form liquid water involves an understanding of thermal energy and the structure of matter. In Chapter 1, the internal or thermal energy of a substance was defined as the total energy possessed by the particles of the substance. This is made up of both kinetic and potential energies. In solids, such as a block of ice, the particles are held firmly in position by the bonds between the particles. The particles contain kinetic energy in the form of vibrational motion, as well as several forms of potential energy.

melting
is a physical process where a solid undergoes a phase change to become a liquid

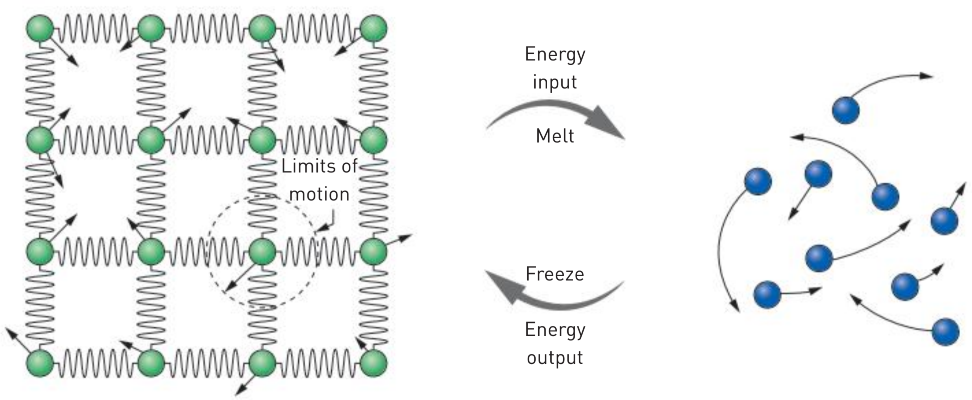

FIGURE 5 Energy is required to partially overcome the attractive forces between molecules in a solid to form a liquid. When it does, it melts (top arrow). That same amount of energy must be removed for freezing (solidification) to take place (bottom arrow).

As the ice is heated at its melting point the molecular forces are no longer strong enough to hold the particles together in fixed positions. The particles break free and can slide past one another – the solid melts. It requires a large amount of energy to break the bonds and increase the potential energy of the particles. When this is occurring, the addition of thermal energy does not go into changing the kinetic energy of the particles but into increasing the potential energy. Since temperature is a measure of the average kinetic energy of the particles, the temperature does not increase. So, when a solid melts by the addition of heat, the potential energy of the particles increases without a change in temperature.

After melting, the addition of heat results in an increase in the kinetic energy (now translational, rotational and vibrational) as well as the potential energies of the liquid. Thus, temperature again rises, as shown in Figure 8 (p. 100).

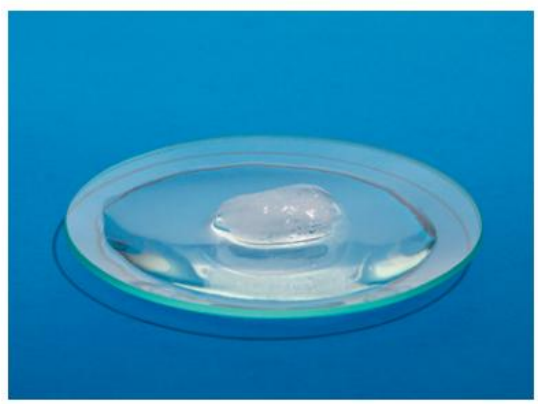

FIGURE 6 As an ice cube melts, thermal energy from the surroundings is transferred to the ice and the water. Although the liquid water has the same mass as the solid ice did, it now has higher thermal energy.

Table 1 shows some real data from a Year 11 class about the heating of ice. You can see that the temperature remains constant at 0 °C for a couple of minutes (t = 3 to 4 minutes) as the ice melts.

TABLE 1 Data of melting ice

t (min)	0	1	2	3	4	5	6	7	8	9	10
T (°C)	− 5	− 3	− 0.5	0	0	2.5	5	15	26	37	48

Vaporisation – from liquid to gas

vaporisation
a physical process where liquid undergoes a phase change to become a vapour (it can include evaporation or boiling)

boiling point
the temperature at which a liquid changes into a vapour when the vapour pressure of the liquid equals the surrounding pressure

As we continue to heat water towards the boiling point, some particles begin to break the cohesion forces holding them together. The forces of attraction between the particles become very weak and the particles move more freely – the substance changes state from a liquid to a gas. This phase change is called **vaporisation**. At a certain temperature, any added thermal energy goes into changing the potential energy of the particles, causing the particles to break the cohesion forces. Again, as in the case of melting, at this point the temperature does not increase as there is no increase in the kinetic energy of the particles. This is shown in Figure 8. This temperature is called the **boiling point** of the liquid. It takes about 2.25×10^6 J of thermal energy to change 1 kg of water at 100°C to steam at 100°C.

The changes in temperature during heating and phase change are shown graphically in Figure 8.

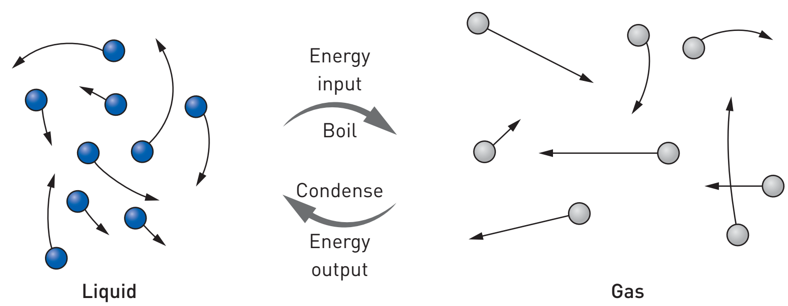

FIGURE 7 As energy is added to a liquid, the particles move faster and eventually leave the surface of the liquid when they have enough energy. Similarly, when the gas is cooled, the particles slow down and eventually condense to form a liquid.

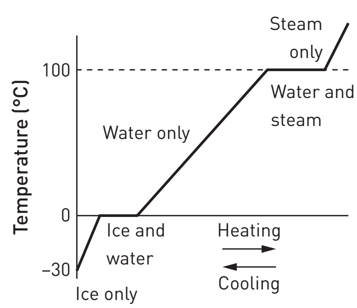

FIGURE 8 Adding heat causes a progression through the three states of water, but there are times when the temperature doesn't change.

Specific latent heats

You have seen that energy is necessary to change a substance from one state to another, even when there is no change in temperature. The amount of energy transfer necessary to change the state of 1 kg of a substance with no change in its temperature is called its specific latent heat.

Latent heat of fusion

'Latent heat of fusion' refers to the amount of energy transfer necessary to change 1 kg of a substance from solid to liquid.

The **specific latent heat of fusion** is the amount of energy required to melt 1 kg of a substance at its melting point.

To change 1 kg of ice at 0°C to water at 0°C requires 3.34×10^5 J of energy. Therefore, ice has a specific latent heat of fusion of 3.34×10^5 J kg^{-1}. Specific latent heats of fusion of other solids are given in Table 2. The word 'latent' is Latin for 'hidden'. It is only hidden in the sense that a substance can take in heat energy without the thermometer registering a change. In that sense, it is hidden as potential energy in the bonds between the particles (rather than in the kinetic energy of the particles). It is not the best word to describe the energy, but for historical reasons it has stuck. The word 'fusion' is from the Latin *fundere*, meaning to melt.

specific latent heat of fusion
the amount of energy required to change 1 kg of a substance from solid to liquid at its melting point (symbol: L_f; unit: J kg^{-1})

Latent heat of vaporisation

Vaporisation is the process of turning a liquid into a gas (vapour). The term 'latent heat of vaporisation' refers to the amount of energy transfer necessary to change 1 kg of a substance from liquid to gas.

The **specific latent heat of vaporisation** is the thermal energy required to change 1 kg of a liquid at its boiling point into a vapour.

As it takes 2.26×10^6 J of thermal energy to change 1 kg of water at 100°C to steam at 100°C we can say the specific latent heat of vaporisation of water is 2.25×10^6 J kg^{-1}. Conversely, this is also the amount of energy that would be released if 1 kg of steam condensed back into water. Specific latent heats of vaporisation of other liquids are given in Table 2.

specific latent heat of vaporisation
the thermal energy required to change 1 kg of a liquid at its boiling point into a vapour (symbol: L_v; unit: J kg^{-1})

TABLE 2 Specific latent heats of some common substances

Substance	Specific latent heat of fusion L_f (J kg^{-1})	Specific latent heat of vaporisation L_v (J kg^{-1})
Mercury	1.18×10^4	2.90×10^5
Lead	2.30×10^4	8.64×10^5
Gold	6.30×10^4	1.64×10^6
Silver	1.05×10^5	2.36×10^6
Alcohol	1.09×10^5	8.70×10^5
Aluminium	1.80×10^5	1.14×10^7
Copper	2.05×10^5	4.82×10^5
Iron	2.76×10^5	6.29×10^6
Water	3.34×10^5	2.26×10^6

Study tip

Note on spelling: *vapour* is British, *vapor* is US. We tend to use the British spelling 'vapour', but when it comes to the process of changing from a liquid to a vapour, it is called *vaporisation* or *vaporization* the world over.

Specific latent heat formulas

Latent heat of fusion

The thermal energy required to melt a mass of a substance at its freezing (or melting) point is given by the equation:

$Q = mL_f$

where Q is the 'heat' (in J), m is the mass of the substance (in kg), and L_f is the specific latent heat of fusion of the substance (in J kg^{-1}).

WORKED EXAMPLE 2.4A

How much energy is required to change a 2.00 kg block of lead to liquid at its melting point?

SOLUTION

From Table 2, the specific latent heat of fusion of lead is 2.30×10^4 J kg^{-1}.

$Q = mL_f$

$= 2.00 \times 2.30 \times 10^4$

$= 4.60 \times 10^4$ J

WORKED EXAMPLE 2.4B

An ice tray containing 200 g of water at 25.0°C is placed in the freezer. How much heat energy has to be removed to change the water into ice at −4.0°C?

(Note: c_{water} = 4180 J kg^{-1} K^{-1}, c_{ice} = 2050 J kg^{-1} K^{-1})

SOLUTION

You need to recognise that there are three cooling stages in this question:

- heat has to be removed to lower the temperature of water from 25°C to 0°C
- more heat has to be removed to freeze the water at 0°C (its melting point) just to overcome the kinetic energy keeping the particles apart – this results in ice at 0°C
- even more heat has to be removed to cool the ice down from 0°C to −4°C.

Note that the specific heat capacity of ice (2100 J kg^{-1} K^{-1}) is different from that of water (4180 J kg^{-1} K^{-1}).

$Q = mc\Delta T + mL_f + (mc\Delta T)_{ice}$

$= 0.200 \times 4180 \times (25.0 - 0) + 0.200 \times 3.34 \times 10^5 + 0.200 \times 2050 \times (4.0 - 0)$

$= 2.1 \times 10^4 + 6.68 \times 10^4 + 1640$

$= 8.94 \times 10^4$ J (3 sf)

Latent heat of vaporisation

The energy required to vaporise a liquid is given by the equation:

$Q = mL_v$

where L_v is the specific latent heat of vaporisation.

WORKED EXAMPLE 2.4C

A beaker contains 150 mL of water at the boiling point. What extra thermal energy is required to vaporise it at 100°C?

SOLUTION

$$
\begin{aligned}
Q &= mL_v \\
&= 0.150 \times 2.25 \times 10^6 \text{ J kg}^{-1} \\
&= 3.38 \times 10^5 \text{ J (3 sf)}
\end{aligned}
$$

Study tip

Making a cappuccino is an example of latent heat of vaporisation by calorimetry experiment. More information can be found on your obook assess.

Latent heats by calorimetry

A simple way to find the latent heat of fusion of ice is to place it in some warm water and note the temperature after the ice melts. To find the latent heat of vaporisation of water to steam, you can bubble some steam through cool water and note its temperature rise and how much steam condenses to water. Both involve calorimetry and are quite simple, although the steam experiment is dangerous as the steam may condense and suck water back into the hot flask and cause it to shatter. Let's look at the fusion of ice.

WORKED EXAMPLE 2.4D

A 25.0 g ice cube at 0°C was placed into 250.0 g of water at 33.5°C in an insulated cup. After the contents reached thermal equilibrium, the temperature was measured to be 22.1°C.

a Calculate the specific latent heat of fusion of ice.

b Calculate the percentage error.

SOLUTION

a

$$
\begin{aligned}
-Q_L &= Q_G \\
-m_{\text{water}} c_{\text{water}} \Delta T_{\text{water}} &= m_{\text{ice}} L_f + m_{\text{ice water}} c_{\text{water}} \Delta T_{\text{ice water}} \\
-m_{\text{water}} c_{\text{water}} (T_f - T_i) &= m_{\text{ice}} L_f + m_{\text{ice water}} c_{\text{water}} (T_f - T_i) \\
-0.250 \times 4180 \times (22.1 - 33.5) &= 0.025 L_f + 0.025 \times 4180 \times (22.1 - 0.0) \\
1.191 \times 10^4 &= 0.025 L_f + 2309.5 \\
0.025 L_f &= 9600.5 \\
L_f &= 3.84 \times 10^5 \text{ J kg}^{-1} \text{ (3 sf)}
\end{aligned}
$$

b

$$
\begin{aligned}
E_a &= |X_O - X_A| \\
E_a &= |3.84 \times 10^5 - 3.34 \times 10^5| \\
&= 5.00 \times 10^4 \text{ J kg}^{-1} \\
E\% &= \frac{E_a}{X_A} \times 100\% \\
&= \frac{5.00 \times 10^4}{3.34 \times 10^5} \times 100\% \\
&= 15.0\% \text{ (3 sf)}
\end{aligned}
$$

CASE STUDY 2.4

Iceberg melting rates

Scientists have been researching the factors affecting iceberg melting for at least 30 years. The melting and breaking-up of polar ice has become an even more important issue since the effects of climate change have been recognised.

It is well known that the most important factor affecting iceberg melting is the temperature of the surrounding fluid. This fluid can be either the air around the exposed part of the iceberg or the water underneath. But other factors include the volume and shape of the icebergs. **The bigger the surface area (and in practice this also means volume), the faster the melting rate.**

When an iceberg melts, it often cracks into two pieces. Depending on the size and shape of these new pieces, it may have a 'rollover'. In Figure 9 you can see icebergs of different sizes, and these will melt at different rates.

FIGURE 9 Icebergs in the Antarctic. Can you predict which of these icebergs will melt faster? It is hard to tell their size in this photo, but they are actually the size of office blocks.

CHALLENGE 2.4

Heat of humans

In 1775, British physicist Dr Charles Blagden was conducting a series of experiments to test the effect of extremely high temperatures on humans. During one of these experiments, Blagden took some friends, a dog and a raw beef steak into a room at 127°C for 45 minutes. They all came out unharmed except for the steak, which was cooked. Consider why this happened.

The snowman in a coat

Which will melt faster – a snowman with or without a coat? The answer is the snowman without a coat.

The snow melts as thermal energy is transferred from the warm air to the ice of the snowman. Anything that can prevent or slow this transfer will slow down the rate of melting. This can be confusing, as a coat is associated with keeping warm. You would normally wear a coat to slow the transfer of thermal energy from your body to the cold outside, but with the snowman it is the other way around. What if the outside was colder than the snowman? In that case, the snowman wouldn't melt at all so a coat would make no difference.

SUGGESTED PRACTICAL

2.4 Observation of phase change – during heating
Go to your obook assess »

CHECK YOUR LEARNING 2.4

Apply, analyse and interpret

1 **Determine** the energy required to melt 2.50 kg of gold at its melting point. (Refer to Table 2 (p. 101) for latent heats of fusion.)

2 Copper has a melting point of 1083°C. **Determine** the energy required to melt 200.0 g of copper originally at 22°C (room temperature).

3 A 2.0 L bottle of water at 20°C is placed in the freezer compartment of a refrigerator. **Determine** how much thermal energy must be removed by the refrigerator to freeze this water.

4 A 25.0 g piece of ice at 0°C was placed into a foam cup of negligible heat content containing 350.0 mL of water at 18.0°C. The final (equilibrium) temperature was 12.0°C. **Determine** the latent heat of the ice.

5 In an experiment to measure the latent heat of fusion of ice, a 31.0 g piece of ice at 0°C was placed into a foam cup of negligible heat content containing 300.0 mL of water at 28.6°C. The final (equilibrium) temperature was 18.4°C.

  a **Calculate** the latent heat of the ice and the percentage error.

  b **Consider** the final temperature if crushed ice was used.

  c If crushed ice was used, would it come to the final temperature any quicker? **Explain** your answer.

6 **Determine** the mass of acetone that can be vaporised by the addition of 20 kJ of thermal energy while at its boiling point of 56°C. (acetone $L_v = 5.18 \times 10^5$ J kg^{-1})

Investigate, evaluate and communicate

7 A class of Year 11 students (in five groups) conducted a latent heat investigation (as outlined in Worked example 2.4D). Table 3 shows their results.

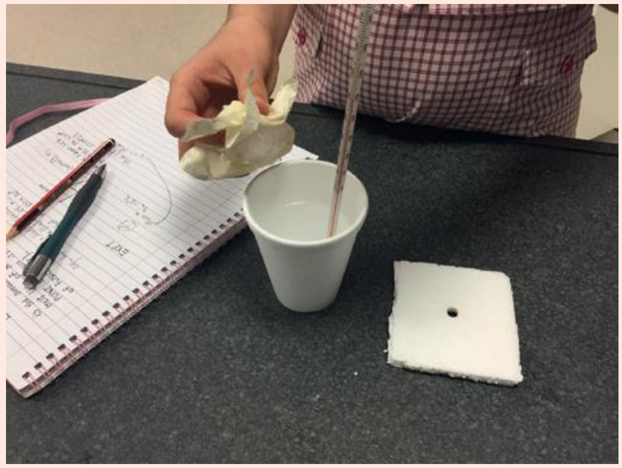

FIGURE 10 In this experiment, the student has ensured the ice is dry and will add the lid promptly to minimise errors.

  a Using the data in the table, **calculate** the specific latent heat of fusion found by Groups 4 and 5 and their percentage error.

  b **Determine** whether the errors for the L_f results are all in one direction. That is, are they all over or all under the accepted value?

  c Based on your answer to **7b**. would you say the errors are random or systematic? **Explain**.

TABLE 3 Class results

Group	m_{ice}	m_{water}	$T_{i\,(water)}$	T_f	L_f	Error (%)
1	19.61	114.16	59.5	39.0	337 433	1.0
2	18.28	94.26	43.0	24.0	310 658	7.0
3	13.96	103.10	58.0	41.0	355 117	6.3
4	21.18	112.44	55.5	35.5		
5	21.23	94.53	52.0	29.0		

Check your obook assess for these additional resources and more:

» Student book questions
Check your learning 2.4

» Suggested practical
2.4 Observations of phase change - during heating

» Challenge
2.4 Heat of humans

CHAPTER 2

Review

Summary

2.1
- The zeroth law of thermodynamics states that the transfer of energy from a system with higher temperature to a system with lower temperature will occur until thermal equilibrium is reached.

2.2
- The specific heat capacity (*c*) of a substance is the quantity of heat required to raise the temperature of 1 kg of the substance by 1°C. It is measured in J kg^{-1} K^{-1}.
- The quantity of energy (*Q*) transferred to or from a substance is given by the equation: $Q = mc\Delta T$, where *Q* is the energy in joules, *m* is the mass of the substance in kg, *c* is the specific heat capacity in J kg^{-1} K^{-1}, and ΔT is the change in temperature in kelvin (or Celsius).

2.3
- In a closed system, the thermal energy lost by one object is equal to the thermal energy gained by the other. This is conservation of energy.
- When two bodies have the same temperatures as a third body, then the two also have temperature equal to each other.

2.4
- To bring about a change of state requires energy (latent heat).
- The energy required to change 1 kg of a substance from a solid to a liquid without a change in temperature is called the specific latent heat of fusion (L_f).
- The energy required to change 1 kg of a substance from a liquid to a gas without a change in temperature is called the specific latent heat of vaporisation (L_v).
- $Q = mL_f$, where L_f is the specific latent heat of fusion measured in J kg^{-1}.

Key terms

- calorimeter
- calorimetry
- conservation of energy
- melting
- specific heat capacity
- thermal equilibrium
- vaporisation
- zeroth law of thermodynamics

Key formulas

Finding the specific heat capacity of a substance	$Q = mc\Delta T$
Finding specific latent heat of fusion	$Q = mL_f$
Finding specific latent heat of vaporisation	$Q = mL_v$

Revision questions

The relative difficulty of these questions is indicated by the number of stars beside each question number: ★ = low; ★★ = medium; ★★★ = high.

Multiple-choice

1 If two objects labelled *B* and *C* are both at thermal equilibrium with object *A*, which of the following must be true?

- **A** Objects *B* and *C* are in thermal equilibrium with each other.
- **B** Object *B* has a higher temperature than object *C*.
- **C** Object *C* has a higher temperature than object *B*.
- **D** Objects *B* and *C* are not in thermal equilibrium with each other.

2 A lead fishing sinker with a mass of 75.0 g and a temperature of 25°C is placed on a block of ice at 0°C, which then melts. If 75.0 g of water at the same temperature were poured on the ice, which of the following is true?

- **A** The water would melt more ice than the lead fishing sinker.
- **B** The water would melt less ice than the lead fishing sinker.
- **C** The water would melt the same amount of ice as the lead fishing sinker.
- **D** Neither the water nor lead fishing sinker would melt any ice.

3 The specific heat of a liquid is 1000 J kg^{-1} K^{-1}. What amount of heat is needed to raise the temperature of 4.0 kg of liquid from 30°C to 40°C?

- **A** 4.0×10^3 J
- **B** 2.0×10^4 K
- **C** 4.0×10^4 J
- **D** 8.0×10^4 K

4 Which one of the following is true about the melting of ice?

- **A** Energy is required to increase the average kinetic energy of water molecules.
- **B** Energy is required to decrease the average kinetic energy of water molecules.
- **C** Energy is required to increase the potential energy between the water molecules.
- **D** No energy is required for this process as it happens spontaneously.

5 A cube of ice is placed in a foam cup and it begins to melt. The air temperature is 23°C. Which one of the following best describes the temperature of the water that is formed?

- **A** less than 0°C
- **B** 0°C
- **C** room temperature
- **D** greater than 0°C but less than room temperature

Short answer

Describe and explain

★ **6** The zeroth law of thermodynamics was invented after the first law of thermodynamics. **Explain** why it is numbered before the first law.

★ **7** **Define** 'specific heat capacity' and 'specific latent heat'.

★ **8** **Define** 'thermal equilibrium' and give an example.

★★ **9** Figure 1 is a heating graph where the lines A and B represent beakers containing either 100 mL or 200 mL of water. **Explain** which line is which.

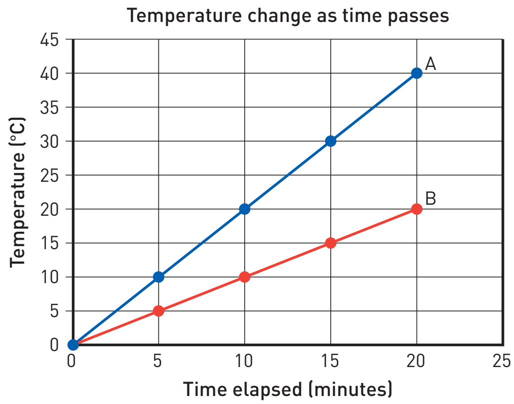

FIGURE 1 Heating graph for beaker A and beaker B

★★ **10** A 70.0 g cube of iron at 90.0°C is placed in contact with a block of aluminium of similar mass at room temperature of 23.0°C. **Calculate** the final (equilibrium) temperature.

★★ **11** A 70.0 g cube of copper at 100.0°C is placed on a 200.0 g piece of lead at room temperature.

- **a** Assuming no heat is transferred to the environment, **calculate** the final (equilibrium) temperature.
- **b** **Calculate** the temperature the copper would have to be raised to so that the final (equilibrium) temperature was 70.0°C.

★★★ **12** **Identify** the mass of steam initially at 130°C that is needed to warm 200 g of water in a 150 g glass container from 20°C to 50°C.

★★★ **13** An electric shower unit is rated at 5 kW. If water enters it at 15°C and leaves it as hot water at the rate of 5 kg per minute, **calculate** the temperature of the hot water.

Apply, analyse and interpret

★ **14** **Determine** the amount of thermal energy needed to raise the temperature of a 250 g piece of copper from −20°C to 25°C.

★ **15** 1500 J of energy is used to heat a 400 g sample of iron initially at 28°C. **Deduce** the final (equilibrium) temperature of the iron.

★ **16** A 2000 J energy supply was used to heat four different masses of the same metal: 100 g, 200 g, 500 g and 1.00 kg.

- **a** If the 100 g mass changed its temperature by 5°C, **determine** what the temperature changes of the other three masses would have been.
- **b** **Identify** the specific heat capacity of the metal.
- **c** **Determine** if the metal is more likely to be copper or aluminium.

★ **17** A student likes to mix iced coffee with their hot coffee drink to cool it down. If the student added 100 mL of iced coffee at 5°C with 250 mL of hot coffee at 70°C, **determine** the final (equilibrium) temperature of the mix. (Specific heat capacity of milk is 3930 J kg^{-1} K^{-1}.)

★ **18** Steam at 100°C will cause much more severe burns than water at 100°C.

- **a** **Explain** in which state (liquid or vapour) the molecules are moving the fastest.
- **b** **Clarify** in which state the molecules have greater potential energy.
- **c** **Consider** why steam burns are more severe than those from water at the same temperature.

★★ **19** 200 g of water at 80°C is mixed with 100 g of gold at 20°C. If the final (equilibrium) temperature is 79°C, **determine** the specific heat capacity of gold.

★★ **20** 250 g of water at 80°C is mixed with 1000 g of aluminium at 20°C and 500 g of zinc also at 20°C. **Determine** the final (equilibrium) temperature of the mixture. (c_{Zn} = 388 J kg^{-1} K^{-1})

★★ **21** A 1.0 kg sample of metal with a specific heat capacity of 500 J kg^{-1} K^{-1} is heated to 100.0°C and then placed in a 50.0 g sample of water at 20.0°C. **Determine** the final (equilibrium) temperature of the metal and the water.

★★ **22** A 2.0 kg copper block at a temperature of 200.0°C is placed in contact with another copper block of the same mass at a temperature of 20.0°C. **Determine** the final temperature when they have reached thermal equilibrium.

★★ **23** A 150 g steel spanner is left in the sun and reaches a temperature of 50°C. It is then placed on the lid of an aluminium toolbox of mass 1.1 kg at a temperature of 20°C. **Determine** the final temperature when the spanner and the toolbox have reached thermal equilibrium.

★★ **24** A 50 g sample of ethanol (alcohol) at −8°C is poured into a cup containing 75 g ethanol at 24°C. **Determine** the final temperature of the mixture.

★★ **25** A mechanic was making up a 1:50 fuel mixture for a two-stroke motor mower. The mechanic mixed 100 mL (88.8 g) of oil at 35.0°C with 4.90 L (3.53 kg) of petrol at 20.0°C. Given that the specific heat capacities of oil and petrol are 1800 J kg^{-1} K^{-1} and 2130 J kg^{-1} K^{-1} respectively, **determine** the final temperature of the mixture.

★★★ **26** The energy released from condensation in thunderstorms can be very large. **Determine** the energy released into the atmosphere for a small storm of radius 1.0 km, assuming that 1.0 cm of rain is precipitated uniformly over this area.

★★★ **27** To help prevent frost damage, 4.00 kg of 0°C water is sprayed onto a fruit tree.

- **a** **Determine** how much heat transfer occurs as the water freezes.
- **b** **Calculate** how much the temperature of the 200 kg tree would decrease if this amount of heat transferred from the tree. (Specific heat capacity of the tree is considered to be 3350 J kg^{-1} °C^{-1} and assume that no phase change occurs.)

Investigate, evaluate and communicate

★★ **28** A 59.7 g piece of metal was placed in boiling water and allowed to reach 100.0°C. The metal was quickly transferred into 60.0 mL of water initially at 22.0°C. The final (equilibrium) temperature rose to 28.5°C. **Solve** the specific heat capacity of the metal and identify the metal from a table of specific heat capacities.

★★ **29** In the graph shown in Figure 2, line B represents the heating curve for water in a beaker on a hotplate. Line A is for an equal mass of another substance. **Solve** the specific heat capacity of substance A.

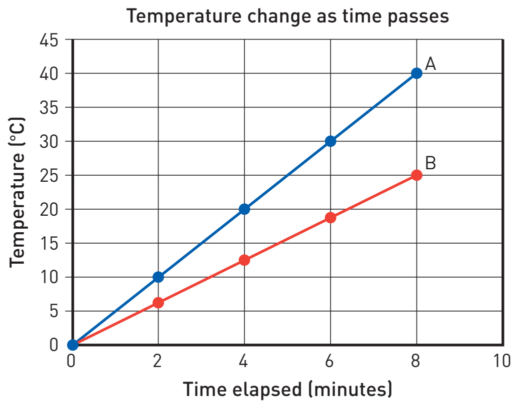

FIGURE 2 Temperature changes

★★ **30** A child wanting to make a cordial ice block places 200 g of cordial at 25°C in the freezer. If the freezer can remove energy at the rate of 25 joules per second, **determine** the time it will it take for the cordial to freeze. (Assume the specific latent heat and specific heat capacity of cordial are the same as water.)

★★ **31** The graph in Figure 3 shows the change in temperature for a solid as it is heated by a 1000 W (1000 J s^{-1}) hotplate and turns into a liquid. **Deduce** which phase has the greater specific heat capacity: solid or liquid.

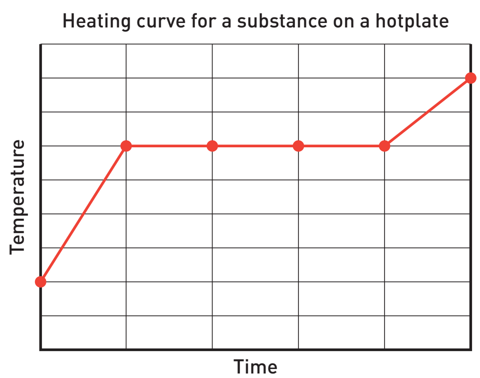

FIGURE 3 Heating curve

★★★ **32** A substance is in the solid form at 0°C. The amount of heat added to this substance and its temperature are plotted in the graph shown in Figure 4. The specific heat capacity of the solid substance is 500 J kg^{-1} K^{-1}. **Determine** the specific latent heat of fusion for the melting process.

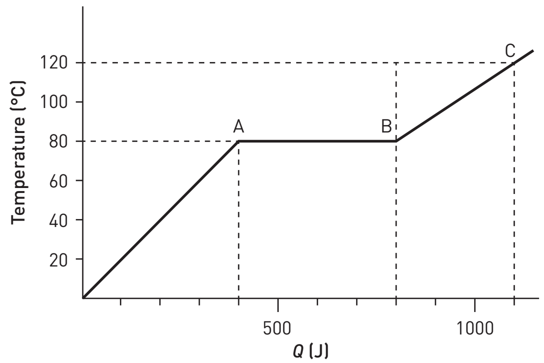

FIGURE 4 Amount of heat added to a substance

★★★ **33** 90.0 g of molten lead at 327.3°C is poured into a 300.0 g casting made of iron initially at 20°C. **Determine** the final temperature of the system.

★★★ **34** Three cubes of iron, aluminium and copper, each of mass 80.0 g, have temperatures of 80°C, 120°C and 180°C respectively. The cubes are pressed together. **Determine** their equilibrium temperature.

★★★ **35** In an insulated vessel, 250 g of ice at 0°C is added to 600 g of water at 18°C.

a **Determine** the final temperature of the system.

b **Determine** how much ice remains when the system reaches equilibrium.

★★★ **36** A block of ice of temperature 0°C and mass 20.0 g was placed in a beaker and weighed. The total mass was 55.0 g. Steam at 110°C was blown onto the ice until the ice completely melted and remained at 0°C. Assuming no loss of heat to the surroundings, **determine** the mass of the beaker and its contents.

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CHAPTER 3

Energy in systems

Energy can be transferred from one object to another by heating it up or by doing work on it. Up until the mid-1800s these two processes were thought to be separate ideas. Heat was regarded as some sort of invisible fluid, a 'caloric fluid' that bodies possessed. Hot bodies, it was believed, contained more of this fluid than cold bodies. When a body was warmed this caloric fluid transferred to the body. But this did not explain why two ice cubes melted when they were rubbed together, or how the pressure from an ice skater's skate blade turns ice into water even though the temperature stays the same.

However, people were able to harness the energy of heat and turn it into useful work, even if they didn't understand the connection. Steam engines were a good example of this. But the need to increase the efficiency of these early steam engines led to further technological advancements such as building the internal combustion engine. More critically, it also led to scientists attempting to understand mathematically the relationship between heating processes and mechanical work. These ideas were eventually brought together in 1843 by James Prescott Joule.

In this chapter we will look at the two ideas: firstly, how heat can be transferred from one object or system to another; and secondly, how mechanical work and heat can be interchanged. This branch became known as 'thermodynamics', a term that comes from Greek words meaning heat and movement.

OBJECTIVES

→ Explain heat transfers in terms of conduction, convection and radiation.
→ Explain that a system with thermal energy has the capacity to do mechanical work.
→ Recall that the change in the internal energy of a system is equal to the energy added or removed by heating plus the work done on or by the system, and recognise this as the first law of thermodynamics and that this is a consequence of the law of conservation of energy.
→ Explain that energy transfers and transformations in mechanical systems always result in some heat loss to the environment, so that the amount of useable energy is reduced.
→ Define efficiency.
→ Solve problems involving finding the efficiency of heat transfers.

Source: *Physics 2019 v1.2 General Senior Syllabus Queensland Curriculum & Assessment Authority*

MAKES YOU WONDER

In this chapter we will be examining ideas that will help to answer questions such as:

→ Why is it cooler in the shade?

→ On cold winter nights how does a quilt keep you warm? Where does it get the energy from?

→ How do you feel the warmth of the electric heater from across the room? Could electric heaters be used in outer space to keep astronauts warm?

→ How does the Sun's heat energy reach Earth?

→ Why doesn't Earth get hotter and hotter as sunlight falls on it?

→ When you rub your hands together on a cold morning your hands become hotter, but where does the energy come from – out of thin air?

→ Can you cool down your house in summer by leaving the refrigerator door open?

→ Car engines convert only about 20% of the energy in petrol to moving along the road. Why doesn't the government pass a law that all the energy has to be used up?

FIGURE 1 The bony plates on a stegosaurus are believed to have acted as cooling fins to regulate temperature, although their primary use was for display. Very big animals lack sufficient surface area for adequate cooling, so this adaptation would have helped.

3.1 Heat transfers

KEY IDEAS

In this section, you will learn about:

+ heat transfer as a process.

heating
the process of transferring thermal energy from a hot object to a cooler one

cooling
the process of transferring thermal energy away from an object to a cooler one

thermal energy transfer
the process of transferring thermal energy from one object to another, also known as heat

Whenever there is a temperature difference, energy transfer occurs. We call this **heating** or **cooling.** Heating may occur rapidly, such as through a frypan, or slowly, such as through the walls of a foam or cardboard coffee cup. We can control the rate of heating by choosing materials such as thick clothing for winter, by controlling air movement such as through the use of fans, or by choice of colour, for example selecting a white car to reflect the Sun's rays. Because so many processes involve heat transfer, it is hard to imagine a situation where no heating or cooling occurs.

All of the questions in the chapter introduction can be answered by considering the process of **thermal energy transfer**. However, every transfer takes place by just three processes: conduction, convection and radiation.

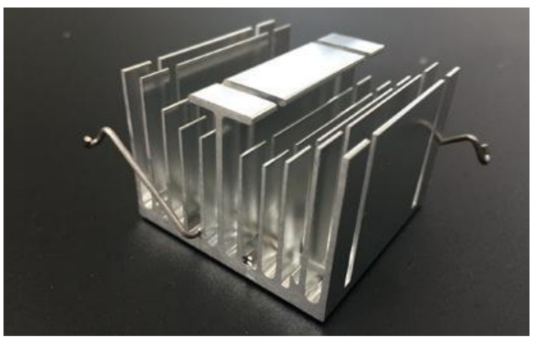

FIGURE 1 Cooling fins of a CPU heat sink

Conduction is the process by which heat is directly transferred or transmitted through the material of a substance when there is a difference of temperature between adjoining regions, without movement of the material.

Convection is the movement caused within a fluid by the tendency of hotter and therefore less dense material to rise, and colder, denser material to sink under the influence of gravity, which consequently results in transfer of heat.

Radiation is the emission of energy as electromagnetic waves.

The next section will look at conduction, convection and radiation in more detail.

CHECK YOUR LEARNING 3.1

Describe and explain

1 **Explain** what happens when an object or system changes temperature.

2 **Recall** two examples that demonstrate how humans can control the heating or cooling of an object.

3 **Identify** the three processes of thermal energy transfer.

4 **Describe** an example from your personal experience for each of the three mechanisms of heat transfer.

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- » Weblink
  Heating and cooling your home
- » Weblink
  Cooling

3.2 Conduction, convection and radiation

KEY IDEAS

In this section, you will learn about:

+ conduction, convection and radiation as processes of heat transfer.

Conduction

conduction
a process in which heat is directly transferred or transmitted through a substance due to a temperature difference between neighbouring regions, without movement of any matter

Conduction is heat transfer through stationary matter by physical contact. The direction of transfer is from more energetic to less energetic particles. It can occur within a substance (such as through a metal rod), or from one substance to another (such as from hot coffee to a spoon).

Conduction within a substance

Conduction (from the Latin word *conducere* meaning 'to lead together') is the process by which thermal energy is transferred through a medium by the vibrating particles of the medium, but without the particles actually moving from one place to another.

In metals, the atoms are held in a lattice arrangement and surrounded by free-moving outer electrons. When heated, the atoms vibrate within the lattice but can't move too far as they are held in place by the 'sea' of free electrons that make up the metallic bond. These mobile electrons can transport energy to neighbouring metal atoms. In non-metals, the atoms are more tightly fixed in their lattice. For example, in diamond, the carbon atoms are held rigidly by strong covalent bonds and the electrons are bound up in the bonds. Hence, diamond is a poor conductor of heat energy.

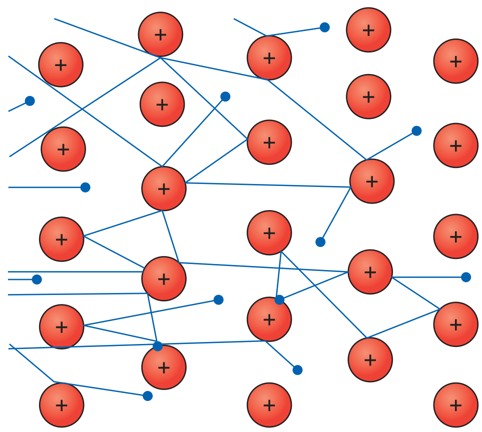

FIGURE 1 Metals have a lot of free-moving electrons that move faster when the metal is heated. The electrons give their energy to neighbouring metal atoms, and so pass the energy on.

Conduction from one substance to another

When a saucepan is placed on a hot stove, or a metal spoon is placed in a hot drink (Figure 2), heat transfer occurs by conduction from one substance to another.

We can look at this process at an atomic level. When a stainless-steel teaspoon is placed in hot water, you can feel that the spoon handle becomes hot. Thermal energy

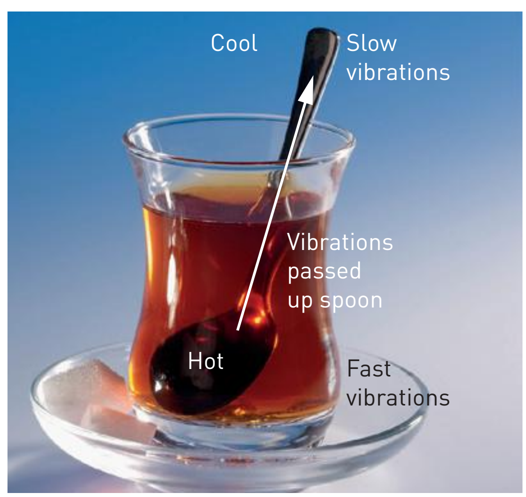

FIGURE 2 Transfer of thermal energy by conduction

travels (as heat) from the hot water up the spoon to your hand. The molecules of the hot water are moving faster than those of the spoon – they have more energy because they are hotter. When these molecules collide with the particles of the spoon, they transfer some of their energy to those iron atoms in the spoon. These atoms in turn vibrate and cause their neighbours to vibrate. This continues until all the thermal energy in the atoms in the spoon and water is in equilibrium. Thermal energy is transferred from the hot water to the spoon, and eventually to your hand.

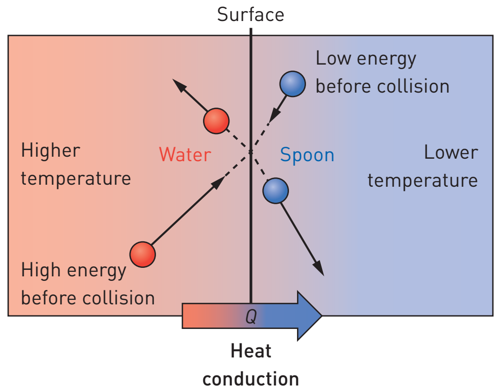

FIGURE 3 Heat conduction for a spoon placed in hot water

convection
a transfer of heat caused by the movement within a fluid of the hotter and less dense material, which rises, and colder, denser material which sinks, under the influence of gravity

free convection
the movement caused within a fluid by the tendency of hotter and therefore less dense material to rise, and colder, denser material, to sink under the influence of gravity, which consequently results in transfer of heat

forced convection
the movement caused within a fluid generated by an external source such as a pump, fan, or suction device

Convection

Convection is another method of heat transfer. The word convection comes from the Latin *convehere*, meaning 'to carry together'. Convection is similar to conduction, but in this case the particles of the materials themselves actually move. While conduction is the transfer of heat by the vibration of particles of the material, convection is the transfer of heat by the movement of particles from one place to another. As solid particles do not move, convection is confined to fluids (liquids and gases).

Convection is driven by large-scale flow of matter. For example, a pot-belly stove placed in the centre of a living room heats the air in its immediate vicinity. This air expands, becoming less dense and thus rising. Cooler surrounding air moves in to replace the hotter air that rises. The rising hot air cools as it goes higher and therefore recirculates, as shown in Figure 4b. Convection currents are thus set up. A similar process happens when water is heated in a saucepan on the stove. If there is no bulk fluid (such as a breeze or water current), the heat conduction between solid and adjacent fluid has to be by conduction only. The motion of the fluid enhances the heat transfer.

Free convection and forced convection

There are two types of convection. **Free convection** (or natural convection) relies on the buoyancy forces developed from differences in density as a result of temperature differences. **Forced convection** comes about by use of a fan, wind or a pump. Isaac Newton developed his law of cooling in 1701 after experiments with a lump of hot iron cooled in a breeze on his window sill. The breeze is an example of forced convection.

radiation
the transfer of energy in the form of electromagnetic waves or moving subatomic particles

electromagnetic radiation
radiant energy consisting of electromagnetic waves, propagated at the speed of light in a vacuum

Radiation

In conduction and convection, the vibration or the movement of particles results in heat energy transfer. But how does heat energy move between places where no particles exist? How does heat energy travel between the Sun and Earth through the vacuum of space?

Where no particles exist, heat is transferred by **radiation**. The word 'radiation' is from the Latin *radiare* meaning 'to emit beams' (like the spokes on a wheel – the Romans called spokes *radii*, which is where the English word 'radius' comes from). Radiation involves the movement of heat energy by waves called electromagnetic waves. These waves travel through space at a speed of 3×10^8 m s^{-1}. We call this **electromagnetic radiation**.

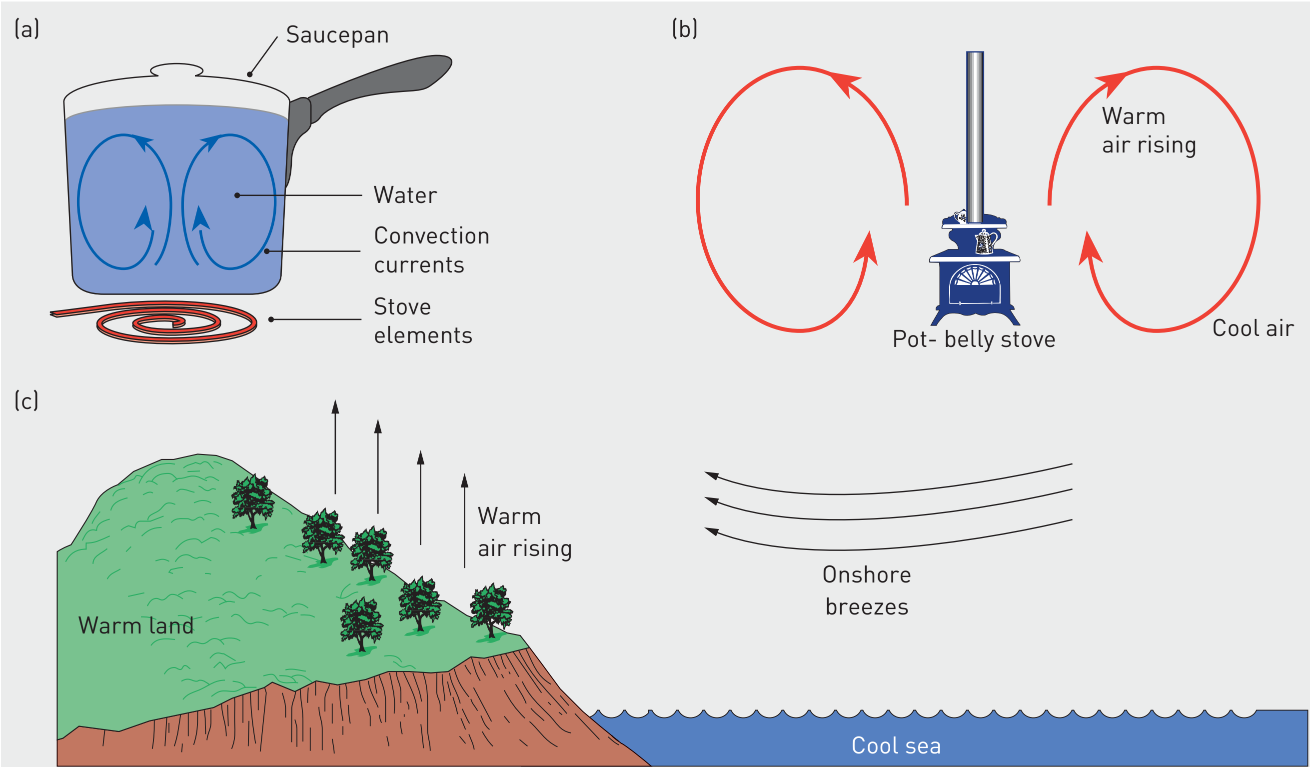

FIGURE 4 (a) Convection currents in a saucepan of water; (b) a pot-belly stove warms a room by setting up convection currents; (c) convection currents arise in the evening of a warm day, because of the difference in temperature between the land and the sea, creating onshore breezes

FIGURE 5 A photo taken from NASA's International Space Station of the sunset over Earth. The Sun emits ultraviolet, visible and infra-red radiation that reach the Earth. About 1000 J of thermal energy from the Sun strikes one square metre (1 m^2) of Earth's surface every second.

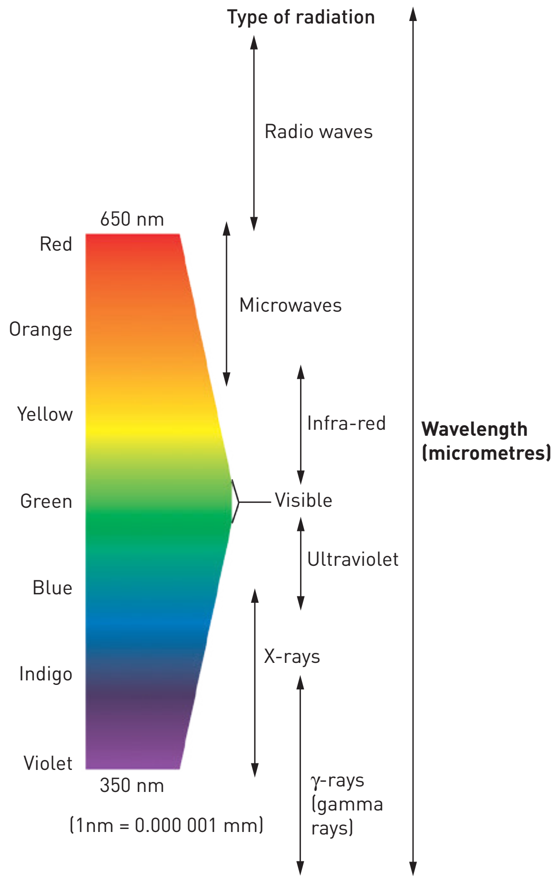

FIGURE 6 Electromagnetic spectrum (note the location of infra-red radiation)

At an atomic level, radiation is due to changes in electron configuration in atoms. When electrons drop from a high-energy shell to a lower one, electromagnetic energy is emitted in the form of radiation. In thermodynamics, we are interested in thermal (infra-red) radiation – radiation emitted by bodies because of their temperature. It differs from X-rays, radio waves, wi-fi and microwaves as they are not related to temperature.

All bodies above 0 K emit thermal radiation. It is considered a surface phenomenon, as atoms inside an object can't get their radiation out. Thermal radiation is usually limited to the top few micrometres of the surface.

This radiant energy is in the form of electromagnetic waves whose wavelength is in the infra-red region. The wavelengths of these waves are longer than those of visible light and therefore cannot be seen. However, they can be detected. You may have seen 'night-vision' goggles used by police, the armed forces or night-time photographers.

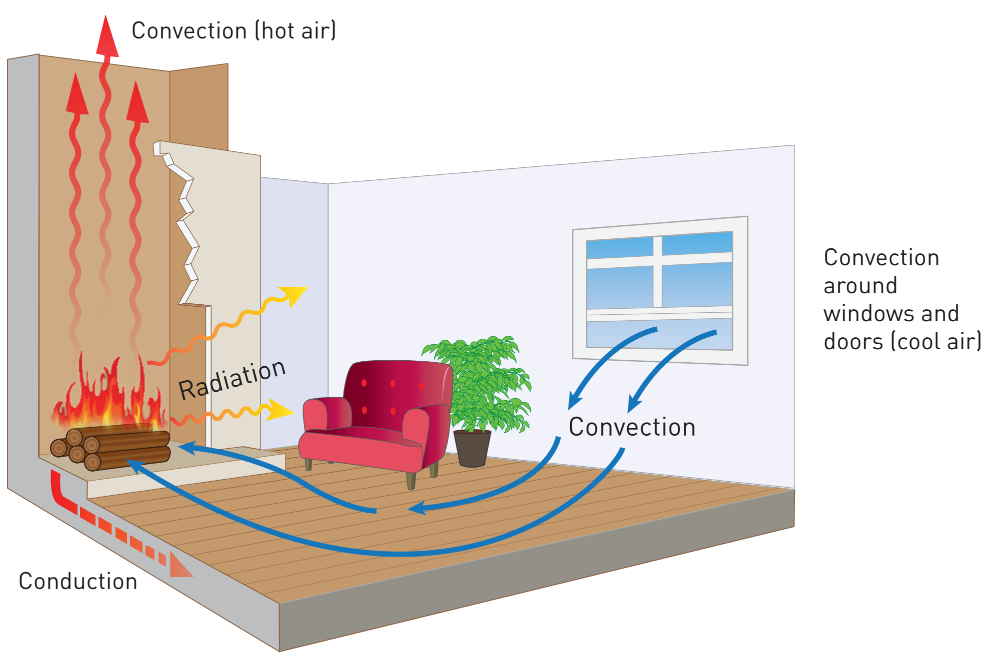

FIGURE 7 Thermal energy transfer in a fireplace

CHALLENGE 3.2

Microwaving grapes

Cut a grape almost half-way through, and then gently pull each half apart slightly so there is a thin bridge of skin between the two halves. Place the grape in a microwave for 10 seconds on high. Can you explain what happens?

CHECK YOUR LEARNING 3.2

Describe and explain

1. When one end of a glass rod is placed in the flame of a Bunsen burner, the other end becomes hot.
   a. **Explain** how the heat energy travels from one end to the other.
   b. **Recall** what other laboratory materials would transfer heat faster.
2. **Explain** why heat energy from the Sun cannot be transferred to Earth by conduction or convection.
3. **Recall** which of these regions of the electromagnetic spectrum has the higher wavelengths: visible or infra-red.
4. **Describe** how the rate of heat production by a surface varies with absolute temperature.
5. **Identify** the advantage of placing the heating element at the bottom of an electric kettle.

Apply, analyse and interpret

6. **Compare** free convection and forced convection.
7. **Consider** the major property that distinguishes radiation from conduction and convection as a means of heat transfer.
8. **Differentiate** between infra-red radiation and visible light.
9. **Deduce** why sleeping under the cover of large trees on cold, clear nights helps to keep horses warm.
10. **Deduce** which travels faster: thermal energy by convection or by radiation.
11. **Classify** these three types of electromagnetic radiation in order of decreasing wavelength: ultraviolet, infra-red, X-rays.
12. Copper makes a good base for saucepans. **Deduce** why the sides are not also made of copper. (There may be economical and weight reasons for this, but you need to develop a good reason in terms of conduction.)

Investigate, evaluate and communicate

13. **Assess** whether it is true that thermal energy is still being emitted as radiation at a temperature of 0°C.
14. The four thermometers in Figure 8 are placed in sunlight for 10 minutes. **Predict** the order from highest reading to lowest after this time. **Explain** your thinking.

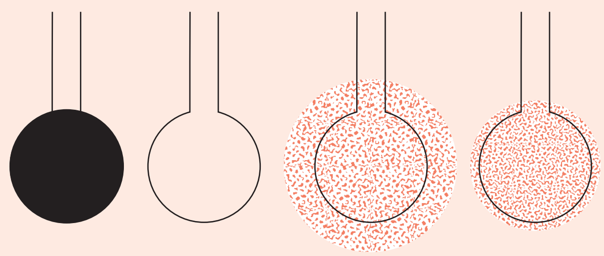

FIGURE 8 Thermometers in sunlight

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3.2 Microwaving grapes

» Video
Thermal conductivity of metals

» Video worksheet
Thermal conductivity of metals

SCIENCE AS A HUMAN ENDEAVOUR

3.3 Heat and work

KEY IDEAS

In this section, you will learn about:

+ how scientific advancements gave an understanding and mathematical articulation of the relationship between heating processes and mechanical work.

In the introduction to this chapter we said there were two ways of adding energy to an object: by heating it or doing work on it.

Up until the mid-1800s, the fields of heat and work (mechanics) were considered to be two separate branches of science. English scientist James Joule (1818–1889) was one of the first scientists to show that heat was a form of energy. He performed an experiment in which falling lead weights turned paddles in water (Figure 2). The work done by these weights caused the water to heat up. Joule said that mechanical energy had been converted into heat. He concluded that heat is a form of energy.

Joule had shown that mechanical energy can be converted into thermal energy. Joule found that the addition of energy to the insulated container (the system) had produced a rise in temperature. The addition of this energy came from the paddlewheels being turned by a falling mass, and it increased the average kinetic energy of the particles in the container. As temperature is the measure of the average kinetic energy of the particles in a system, there is a resultant temperature increase. But Joule knew full well that he could have increased

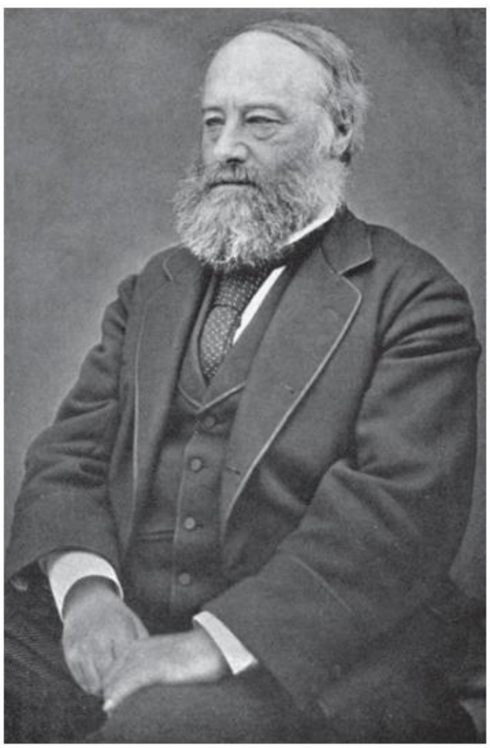

FIGURE 1 James Prescott Joule, an English physicist and mathematician, concluded that mechanical energy can be converted into thermal energy.

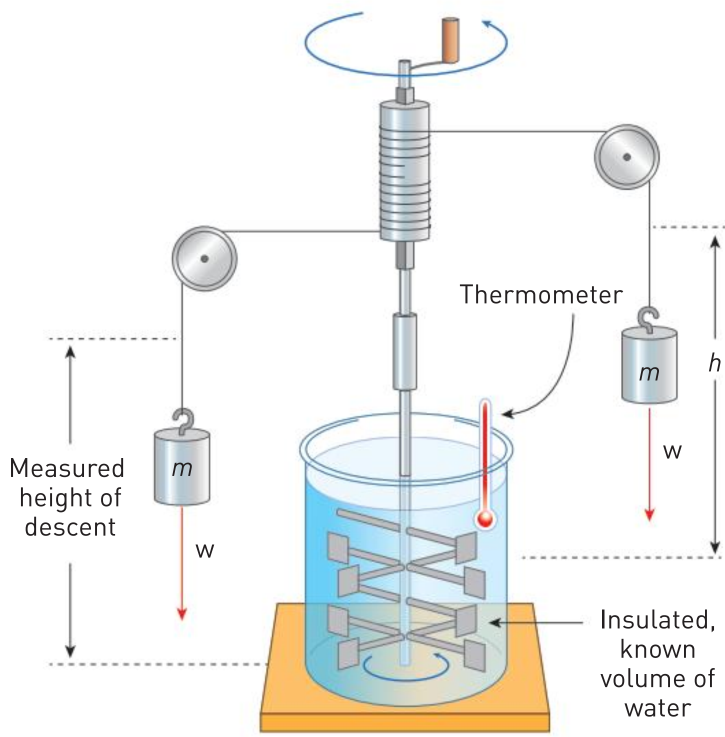

FIGURE 2 A schematic diagram of Joule's apparatus, which was used to establish the equivalence between work and heat (between mechanical and thermal energy)

the temperature of the water by heating it with a flame and the result would have been the same. He understood that heat and work are essentially equivalent.

This also implies that the reverse is true. Thermal energy can be converted into mechanical energy and can do mechanical work. For example, a car engine burns fuel for heat transfer into a gas that exerts a force on the pistons to make them move. This movement is relayed to the car's wheels so that it can travel along the road. We can say that a system with thermal energy has the capacity to do work.

Understanding these relationships opened the door for the development of the science of thermodynamics in the second half of the nineteenth century.

FIGURE 3 A car engine converts thermal energy into a gas that exerts force on the pistons to make them move.

Faraday's ideas about heat conservation

In 1859, Michael Faraday investigated whether an object dropped from a great height would warm up as it hit the ground. He reasoned that there may be some conversion of energy to heat. He dropped a bag of lead shot (like lead sinkers used in fishing), but was unable to detect any temperature rise. He tried to publish his 'null' results and said that perhaps a height of 36 foot (12 metres) was not enough. Mathematics professor George Stokes convinced Faraday not to publish his report because Stokes believed the theory was wrong. But despite the null result, Faraday's theory wasn't wrong; mechanical energy can be converted into heat.

CHECK YOUR LEARNING 3.3

Describe and explain

1 **Identify** what effect there would be on Joule's experiment if the mass fell rapidly, hitting the floor with substantial speed, and this was ignored.
   - A Nothing. The loss in gravitational potential energy would still be the same.
   - B Nothing. The kinetic energy is converted to heat when the mass hits the floor.
   - C Less heat would be generated in the water.
   - D The water would not have time to heat up.

2 **Decide** what forms of energy transfer occur as lead shot falls to the ground and gives up its mechanical energy as heat.

3 **Explain** how Joule brought the two sciences of heat and mechanics together.

Apply, analyse and interpret

4 Students carried out an experiment in which they let a sample of lead shot fall from a large height and stop on impact. The gravitational potential energy of the lead shot at the top was transformed to kinetic energy at the bottom and then, on impact, into thermal energy. The process from E_p to thermal energy (Q) is unlikely to be 100% efficient. **Determine** the percentage efficiency given the following data: mass of lead, m = 500.0 g; fall height, h = 200.0 m; temperature change, ΔT = 22.9°C to 26.0°C; specific heat of lead 130 J kg^{-1} K^{-1}; g = 9.8 m s^{-2}. Note: don't expect the efficiency to be much more than 25%.

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- » Increase your knowledge: Heating lead shot
- » Weblink: Michael Faraday
- » Weblink: Joule

3.4 Changes in internal energy

KEY IDEAS

In this section, you will learn about:

+ change in temperature from work done
+ the first and second laws of thermodynamics.

In Chapter 1 we defined internal energy as the sum of the microscopic kinetic and potential energies of all the particles. We said that it could also be called thermal energy in this context. In this section we will look at how thermal energy can be changed and what use we can make of it.

If you've ever pumped up the tyres on a bicycle or pumped up a ball, you may have noticed that the bike pump gets hot. It seems that compressing the air inside a pump causes heating. Your arm muscles do work on the gas and the gas heats up. If you leave the same pump lying in sunlight it also gets hot. Heat energy from the Sun is transferred into the gas and heats it up. So, you can heat the pump up in two ways: by doing work on it and by adding heat. Does that mean heat and work are interchangeable? That is, can one form of energy be transformed into the other because they both change internal energy (as measured by the temperature)?

If the pump feels hot, how do you know if it was heated by work done on it by your muscles, or by the Sun? You can't tell – the path by which the pump gets hot is unknown, and you can't tell unless you see what happened beforehand.

FIGURE 1 Pumping up a ball makes the pump hot. The pump also gets hot if it is left in the Sun.

First law of thermodynamics

We can develop a relationship between heat, work and internal energy. Firstly, we should call the bike pump the 'system' so that we can generalise later. The internal energy of the gas in the pump (the system) has increased because it is hotter – but this could have come from heat added from a high temperature source (the Sun), or by work done by your muscles on the system. Either way, it results in higher internal energy for the gas inside.

To the initial amount of internal energy in the system, U_i, we can add the net amount of heat, Q, and the net amount of work, W, which gives us the final internal energy, U_f. This can be stated as: $U_i + Q + W = U_f$. This equation can be rearranged to: $U_f - U_i = Q + W$, or by letting $U_f - U_i = \Delta U$:

$$\Delta U = Q + W$$

We can summarise this as: the change in internal energy of a system is equal to the energy added or removed by heating plus the work done on or by the system.

This is an interpretation of the **first law of thermodynamics**.

This conservation law states that the total energy of a system remains constant; energy can neither be created nor destroyed, rather, it transforms from one form to another.

first law of thermodynamics during an interaction between a system and its surroundings, the amount of energy gained by the system must be exactly equal to the amount of energy lost by the surroundings

Thermodynamic energy model

As discussed in the previous section, James Joule increased the temperature of water by using a paddlewheel in the water turned by a falling weight. As the weight fell to the floor, it gave up some of its gravitational potential energy and did work on the system (the water). This energy was transformed into thermal energy in the water. In other words, its internal energy increased. In the case of the bicycle pump mentioned earlier, the internal energy (thermal energy) of the system (the bike pump) was increased by adding heat to it (from the Sun) or by doing work on it (using your muscles).

The diagram in Figure 2 is called the thermodynamic energy model as it shows the two inputs (heat in, and work done on the system) and the two outputs (heat out, and work done by the system).

Study tip

The syllabus requires you to understand the first law of thermodynamics and recognise it as a consequence of the law of conservation of energy.

Conventions

In the thermodynamic energy model:

- Q_{in}, Q_{out}, W_{in}, W_{out} are all positive and the in/out arrows show direction.
- Q_{net} (or Q) = $Q_{in} - Q_{out}$.
- W_{net} (or W) = $W_{in} - W_{out}$.
- If Q positive, there is net heat in (added).
- If Q is negative, there is net heat out (removed).
- If W is positive, there is net work in (done on the system).
- If W is negative, there is net work out (done by the system).

We can represent the net energy quantities as follows:

Net heat energy is Q_{net} (or just Q) = $Q_{in} - Q_{out}$

Net work is W_{net} (or just W) = $W_{in} - W_{out}$

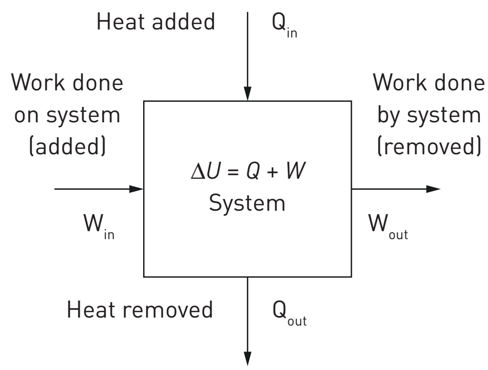


FIGURE 2 Thermodynamic energy model

WORKED EXAMPLE 3.4A

Complete the values in Table 1 (all values are in kJ).

TABLE 1

Q	W	U_i	U_f	ΔU
	6		35	24

SOLUTION

$\Delta U = U_f - U_i = Q + W$

Calculate Q:

$$\Delta U = Q + W$$
$$24 = Q + 6$$
$$Q = 18$$

Calculate U_i:

$$\Delta U = U_f - U_i$$
$$24 = 35 - U_i$$
$$U_i = 11$$

TABLE 2 The completed table

Q	W	U_i	U_f	ΔU
18	6	**11**	35	24

WORKED EXAMPLE 3.4B

A foam cup is filled with hot water and allowed to cool while being stirred by a paddlewheel. Initially the water has an internal energy of 200 kJ, and while cooling it loses 150 kJ of heat. The paddlewheel does 25 kJ of work on the water.

1 Calculate the change in internal energy of the water.

2 Calculate the final internal energy of the water.

SOLUTION

Known values:

U_i = 200 kJ

W = +25 kJ (positive as work is done on the water)

Q_{net} = –150 kJ (negative as the energy is being lost or removed from the system)

1 Calculate ΔU:

$$\Delta U = Q + W$$
$$= (-150) + (+25)$$
$$= -125 \text{ kJ}$$

The change in internal energy of the water is –125 kJ. The negative sign means it has lost 125 kJ.

2 Calculate U_f:

$$\Delta U = U_f - U_i$$
$$-125 = U_f - 200$$
$$U_f = 200 - 125$$
$$= 75 \text{ kJ}$$

The final internal energy of the water is 75 kJ.

WORKED EXAMPLE 3.4C

A pump full of compressed gas is allowed to expand and 80 kJ of work is done by the gas on an object in the lab. At the same time, the gas is warmed by the addition of 100 kJ of heat energy. If the initial internal energy of the gas is 500 kJ, calculate the final internal energy.

SOLUTION

Known values:

$U_i = 500$ kJ

$W = -80$ kJ (negative as work is done by the gas)

$Q_{net} = +100$ kJ (positive as the energy is added to the system)

1 Calculate ΔU:

$\Delta U = Q + W$

$\Delta U = +100 + -80$

$\Delta U = +20$ kJ

The positive sign means it has gained 20 kJ.

2 Calculate U_f:

$\Delta U = U_f - U_i$

$+20 = U_f - 500$

$U_f = +20 + 500$

$= +520$ kJ

The final internal energy is +520 kJ. We can leave the positive sign out as internal energy is always positive. The answer can be written as 520 kJ.

Study tip

Two worked examples looking at situations where there is some heat in and some heat out can be found on your obook assess.

Study tip

There is also a second and third law of thermodynamics. More information can be found on your obook assess.

CHECK YOUR LEARNING 3.4

Describe and explain

1 **Identify** the first law of thermodynamics and use an example to **explain** the main idea.

2 **Explain** the difference between 'work done on a system' and 'work done by a system'.

3 **Calculate** how much heat transfer occurs from a system if its internal energy decreased by 220 J while it was doing 100 J of work.

4 **Calculate** the change in internal energy of a system that does 1.20 MJ of work (out) while 4.8 MJ of heat transfer occurs (out) to the environment. Assume no other changes (such as temperature or by the addition of fuel) take place. Note that mega (M) = 10^6.

Apply, analyse and interpret

5 **Determine** the missing values in Table 3 (all values in kJ).

6 **Deduce** how much heat transfer occurs from a system if its internal energy decreased by 350 J while it was doing 50 J of work.

TABLE 3

	Q	W	U_i	U_f	ΔU
a	–10	25		4	–15
b		–12	3		32
c	25	–15		24	10
d		–18	6		20
e	5		20		35
f	25	10		40	
g	–9			12	–15

Check your obook assess for these additional resources and more:

- Student book questions
  Check your learning 3.4
- Increase your knowledge
  Worked examples
- Increase your knowledge
  The laws of thermodynamics
- Weblink
  Thermodynamics

3.5

Heat engines

KEY IDEAS

In this section, you will learn about:

- how a system with thermal energy has the capacity to do work
- how energy transfers and transformations in mechanical systems always result in some heat loss to the environment, so that the amount of useable energy is reduced
- efficiency
- solving problems involving finding the efficiency of heat transfers.

It is fairly easy to produce thermal energy from work. Rub your hands and they get hot. Hit a nail with a hammer and the nail gets hot. However, it is more difficult to do the reverse – to get usable energy out of heat.

FIGURE 1 The Drinking Bird is a device that turns heat into useful work. Albert Einstein was fascinated by a toy Drinking Bird he saw when he visited Shanghai, China, in 1922. He puzzled over how it worked.

You may have seen a toy called the Drinking Bird (Figure 1). It is a hollow glass device with a small amount of a low boiling point organic liquid (usually dichloromethane) in the bulb at the lower end. When its felt-covered face dips into a glass of water, the water evaporates into the air in the room and cools the liquid inside the bird. Sweat on your skin works in the same way – as the sweat evaporates, it cools your skin. With the Drinking Bird, the cooling effect reduces the pressure in its head and draws some liquid up the neck. This makes it top heavy, so it tilts over and dips its face in more water, and the process cycles over and over again. The Drinking Bird uses the heat from the environment to produce useable work (dunking up and down).

What makes the Drinking Bird interesting for our work in physics is that it is an example of a **heat engine**. A heat engine receives heat from a high temperature source and converts part of this heat into work, rejecting the remaining waste heat to a low temperature 'sink'.

In general, we can say that if a system has thermal energy then **mechanical work** can be extracted, providing a lower temperature cold reservoir (heat sink) is available.

In the Drinking Bird, the air in the room is the high temperature reservoir (heat source) that supplies energy in the form of heat. The bird bobbing up and down converts part of the heat energy to work, and the liquid in the bird is a low temperature reservoir that acts as the heat sink. Note that only a part of the heat energy gets converted to useful work. Note also that the device needs a cold reservoir (the heat sink) and without these conditions being met, you don't have a heat engine.

Figure 2 is an **energy transfer diagram** for a heat engine such as the Drinking Bird. The **hot** reservoir is the warm room at temperature T_H (around 25°C), and the **cold** reservoir is the cooled liquid inside the bird's head at a temperature T_C (usually several degrees below T_H). The engine is the bird itself, and the work done by the system is the kinetic energy of movement as it bobs up and down. Note that the symbols used earlier for heat in and heat out (Q_{in} and Q_{out}) have been replaced by Q_H and Q_C. They mean the same thing and have the same sign conventions. It is common in university texts to make this change when discussing heat engines as it brings uniformity to the treatment of heat engines and the reverse of heat engines, which are called 'heat pumps'.

heat engine
a device that receives heat from a high temperature source and converts part of this heat into work, rejecting the remaining waste heat to a low temperature 'sink'

mechanical work
the capacity of a system with thermal energy

energy transfer diagram
a diagram that summarises all the energy transfers taking place in a process: the thicker the line or arrow, the greater the amount of energy involved

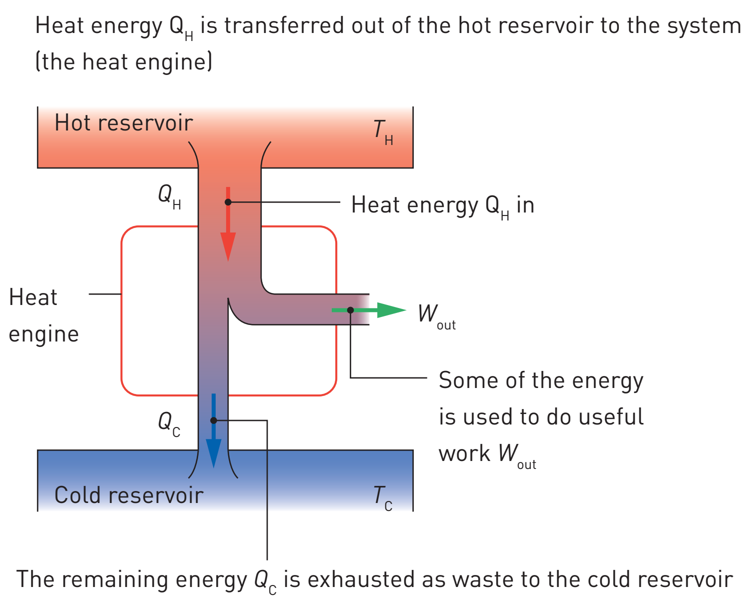


FIGURE 2 Energy transfer diagram for a heat engine such as the Drinking Bird.

Figure 3 is another energy transfer diagram of a heat engine. It shows a hot reservoir at the top (in red), which could be a fire from a fuel such as coal, oil or wood. The heat energy coming out of the hot reservoir, Q_H, is added to the heat engine 'system' (the red box). Some of this is transformed into useful work that leaves the system, W_{out}. As the system uses this energy to do work on something else (such as moving a piston), we say work is done 'by' the system. At the bottom of Figure 3 we can see the energy that goes into the cold reservoir, Q_C, as waste.

In all of these heat engines we assume they have reached a stable temperature and thus there is no change in internal energy ($\Delta U = 0$). We can modify our formula by letting $\Delta U = 0$ to give:

$$\Delta U = Q + W$$
$$0 = Q + T$$
$$W = -Q$$

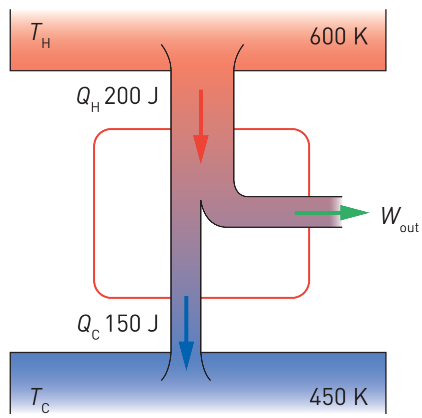


FIGURE 3 An energy transfer diagram that shows specific energy values.

In other words, the work out equals the net heat lost.

Let's look at Figure 3 in more detail, because this energy transfer diagram that has some numbers to show the amount of energy at each stage.

The heat energy coming out of the hot reservoir, Q_H, into the system (red box) is 200 J. The work done by the system is labelled W_{out}. The energy that goes out of the system into the cold reservoir, Q_C, is 150 J of waste heat. This means 50 J was sent out of the system as useful work.

Study tip

One of the skills you should develop in this unit regarding energy transfer diagrams is the ability to interpret, describe, explain and draw them. There is no need to colour an energy transfer diagram.

Calculating work output, W_{out}, using the data and formula is straightforward:

Q_{in} = 200 J; Q_{out} = 150 J (these values are always positive)

$$Q_{net} = Q_{in} - Q_{out}$$
$$= 200 - 150$$
$$= +50 \text{ J}$$

(positive means a net gain of heat into the system)

$$W = -Q_{net}$$
$$= -50 \text{ J}$$

(the negative means work was done by the system, or net work was 'out').

For a heat engine there is no change in temperature and thus no change to internal energy so ΔU should equal zero:

$$\begin{aligned}\Delta U &= Q + W \\ &= +50 + -50 \\ &= 0\end{aligned}$$

Efficiency

In Figure 3, not all the heat extracted from the hot reservoir (200 J) was transformed into work. Only 50 J was transformed, and the other 150 J was wasted. In other words, 50 J of the 200 J that came in was transformed to useful work. This 50 J represents 25% of the heat extracted. This 25% is called the heat engine's **thermal efficiency**. It has the symbol η (lower case Greek eta).

thermal efficiency
the ratio of useful work out of a machine or in a process, total energy expended or heat taken in; often expressed as a percentage (symbol: η)

Energy transfer diagrams were used in the discussion to show the input and output of energy into a mechanical system. They are sometime called 'thermal efficiency diagrams' as they show graphically where non-useful energy transfer has taken place. The greater this non-useful transfer of energy, the less efficient the heat engine is. Figure 4 shows the three main components of energy transfer: in, out and waste.

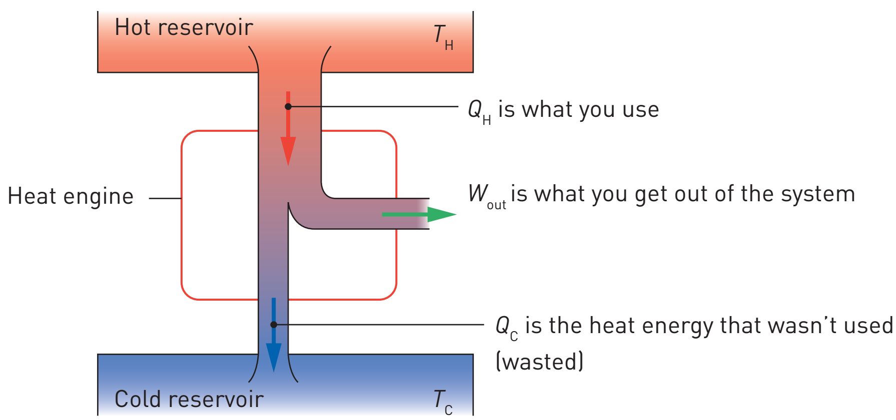


FIGURE 4 The various destinations of heat in a thermal transfer (energy efficiency) diagram

We can develop a formula for thermal efficiency:

$$\eta = \frac{\text{energy output}}{\text{energy input}} \times \frac{100}{1}$$

This thermal efficiency formula can be applied to the example:

$$\eta = \frac{50}{200} \times \frac{100}{1} = 25\%$$

FIGURE 5 Homer Simpson used a Drinking Bird toy to press the 'Y' key on his computer in the 'Fat Homer' episode of *The Simpsons*.

Study tip

The car engine is another example of a heat engine. Further information can be found on your obook assess.

Can you harness any energy from the Drinking Bird toy? The heat that flows out of the hot reservoir in the bird is 4.5×10^3 J, and 1.05 J of mechanical work is done. We can calculate the thermal efficiency for the Drinking Bird:

$$\eta = \frac{\text{energy output}}{\text{energy input}} \times \frac{100}{1}$$
$$= \frac{1.05}{4.5 \times 10^3} \times \frac{100}{1} = 0.02\%$$

This is very poor thermal efficiency. A car engine in contrast has an efficiency of about 20%.

WORKED EXAMPLE 3.5

Figure 6 shows the thermal transfers for a heat engine.

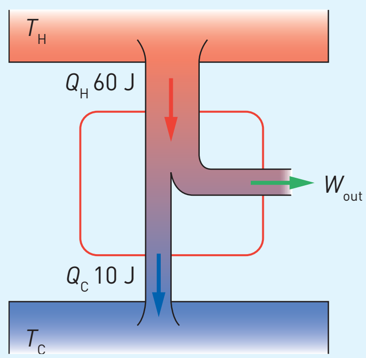


FIGURE 6

1 Calculate the amount of work out of the system.
2 Calculate the thermal efficiency.

SOLUTION

1 Amount of work out:

$$W = -Q_{net}$$
$$= -(Q_H - Q_C)$$
$$= -(60 - 10)$$
$$= -50 \text{ J}$$

(The value is negative so this is work done **by** the system, or 50 J **out**.)

2 Thermal efficiency:

$$\eta = \frac{\text{energy output}}{\text{energy input}} \times \frac{100}{1}$$
$$= \frac{50}{60} \times \frac{100}{1} = 83\%$$

Note that we don't include the negative sign for 'energy out' (W_{out}).

Examples of heat engines

Steam engines

The steam engine is an example of a heat engine, and it powered the industrial revolution. Burning coal or wood in a steam engine turns water into steam. This is the source of thermal energy (T_H), so all we need is a cold reservoir (T_C, the heat sink) to extract mechanical work. The high-pressure steam pushes a piston back and forth, and in so doing it gives up some of its energy as useful work (W_{out}). The remainder of the thermal energy (Q_C) is passed on to the cold reservoir (the environment – in this case, the atmosphere as waste heat). Useful work is produced, but there is always a lot of wasted energy in the form of heat pollution. A steam engine's efficiency (η) is about 8%.

FIGURE 7 A steam train uses the thermal energy of the coal to produce useful work. A steam engine is a good demonstration of the heat engine principles.

CHECK YOUR LEARNING 3.5

Describe and explain

1 **Define** efficiency.

2 **Construct** a simple thermal efficiency diagram and state what the arrows represent.

3 **Explain** what is meant by a hot reservoir and cold reservoir.

4 **Recall** an example of a heat sink.

5 **Calculate** the thermal efficiencies of the four systems in Figure 8.

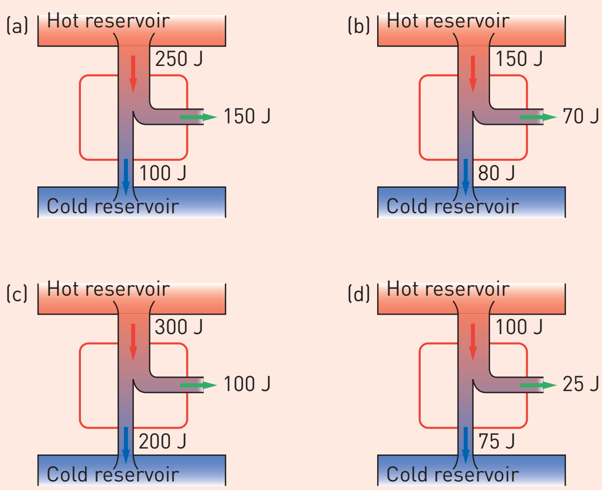


FIGURE 8 Four energy transfer diagrams

Apply, analyse and interpret

6 **Deduce** whether the temperature of a can of soft drink increases as it falls from the top of a tall building. **Explain** your answer.

7 A car engine with a thermal efficiency of 20% does 2000 J of work. **Determine** how much heat energy is:

a taken from the hot reservoir.

b exhausted to the cold reservoir (air).

Evaluate, investigate and communicate

8 **Assess** whether the following claim is valid: 'A heat engine does 10 kJ of work (out) on an input of 30 kJ while 40 kJ of heat transfers to the environment.'

9 **Assess** the result of this scenario: on a hot day, a student turns their fan on when they leave their bedroom in the morning. When they return in the afternoon, **determine** if the room will be cooler or hotter than it would have been if the fan was left off. Assume the window and doors were closed.

10 **Predict** which room will have the higher temperature in this scenario: there are two identical rooms, one with a refrigerator in it and the other without. In the room with the refrigerator, the refrigerator is left running but with the door open.

Check your obook assess for these additional resources and more:

» Student book questions
Check your learning 3.5

» Increase your knowledge
The car engine as a heat engine

» Increase your knowledge
Science as a human endeavour: energy transfers and efficiency

» Weblink
Heat engines

CHAPTER 3

Review

Summary

3.2
- Conduction is the process where heat energy is transferred through a medium by the vibration of the particles of the medium.
- In conduction, the particles of the medium do not travel with the heat flow.
- Insulators are materials that have very low thermal conductivity.
- Convection is the process where heat energy is transferred through a medium by the movement of the particles of the medium. This movement of particles sets up convection currents.
- Radiation is the transfer of heat by means of electromagnetic waves, in particular, infra-red waves.
- The transfer of heat energy by radiation does not require a medium.

3.4
- The change in the internal energy of a system is equal to the energy added or removed by heating plus the work done on or by the system (this as the first law of thermodynamics and this is a consequence of the law of conservation of energy) $\Delta U = Q + W$.

3.5
- A system with thermal energy has the capacity to do mechanical work.
- Energy transfers and transformations in mechanical systems always result in some heat loss to the environment, so the amount of useable energy is reduced.
- Efficiency is the ratio of useful work performed by a machine or in a process to total energy expended or heat taken in.

Key terms

- conduction
- convection
- cooling
- electromagnetic radiation
- energy transfer diagram
- first law of thermodynamics
- forced convection
- free convection
- heating
- heat engine
- mechanical work
- radiation
- thermal efficiency
- thermal energy transfer

Key formulas

First law of thermodynamics	$\Delta U = Q + W$
Thermal efficiency	$\eta = \frac{\text{energy output}}{\text{energy input}} \times \frac{100}{1}$

Revision questions

The relative difficulty of these questions is indicated by the number of stars beside each question number: ★ = low; ★★ = medium; ★★★ = high.

Multiple-choice

1 Convection can NOT occur in which one of the following substances?

- **A** water
- **B** ice
- **C** steam
- **D** water vapour

2 A metal rod is placed between a heat source at 200°C and a heat sink at 20°C. During time t, an amount of heat Q is transferred from the source to the sink. If the metal rod is replaced by another made of the same material twice as thick, determine how much heat will be transferred during the same amount of time t.

- **A** more than Q
- **B** less than Q
- **C** Q
- **D** can't tell

3 When we stand on a floor tile in bare feet, then on a piece of carpet in the same room, the floor tile feels much colder than the carpet. This happens because of the difference in:

- **A** specific heat
- **B** temperature
- **C** thermal conductivity
- **D** latent heat

4 During an energy transfer process, 1000 J of heat are removed from a gas while 100 J of work is done by the gas. What is the change in internal energy of the gas?

- **A** +1100 J
- **B** +900 J
- **C** −900 J
- **D** −1100 J

5 A sample of hydrogen gas is held in a sealed container. The internal energy of it is increased by 800 J. If the net amount of work done on the sample by its surroundings was 500 J, how much heat was transferred between the gas and its environment?

- **A** 1300 J absorbed
- **B** 300 J absorbed
- **C** 300 J dissipated
- **D** 130 J dissipated

Short answer

Describe and explain

★ **6** **Explain** why convection occurs in fluids but not in solids.

★ **7** **Explain** how a blanket keeps you warm during cold winter nights.

★ **8** **Explain** why an iron rod at 1000 K is red-hot while a similar rod at 2000 K is white-hot.

★★ **9** If small blocks of ice are placed in a test tube with water (as shown in Figure 1) and heated, the ice will float at the top as ice is less dense than water. **Explain** the process by which the ice obtains heat energy needed to melt.

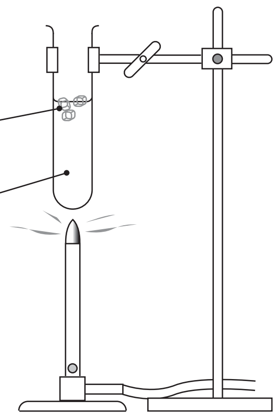


FIGURE 1 The ice will float at the top as ice is less dense than water

★★ **10** **Describe** how the Sun's heat energy reaches Earth.

★★ **11** **Explain** the purpose of a computer's central processing unit having a big metal 'heat sink' and fins with a large surface area attached.

★★ **12** **Explain** whether Earth would be warmer or cooler without the atmosphere.

★★ **13** A steam engine does 4000 J of work while exhausting 1500 J of waste heat.

- **a** **Calculate** the engine's thermal efficiency.
- **b** **Construct** an energy transfer diagram of the situation.

★★ **14 Calculate** the missing quantities in each of the four energy transfer diagrams in Figure 2.

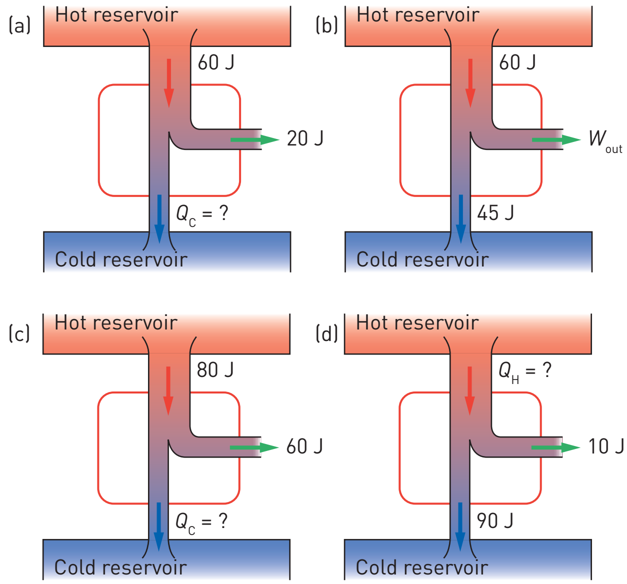


FIGURE 2 Four energy transfer diagrams

Apply, analyse and interpret

★ **15 Deduce** how you feel the warmth of an electric heater from across the room.

★ **16** A 3 m × 3 m brick wall is 30 cm thick. The temperature of the exterior is 5°C and the internal temperature is 28°C. **Deduce** in which direction heat will flow, and by what mechanism.

★★ **17 Infer** why, on a cold winter's morning, a metal spoon feels colder than the table it rests on.

★★ **18 Determine** how much heat transfer occurs from a system if its internal energy decreased by 150 J while it was doing 60 J of work.

★★ **19** A system does 30 MJ of work while 12 MJ of heat transfer occurs to the environment.

- **a Calculate** the change in internal energy of the system (assuming no other changes such as in temperature or by the addition of fuel).
- **b Determine** the percentage efficiency.

★★★ **20 Infer** why knitted woolen jumpers keep you warm in winter. Clarify where the heat comes from.

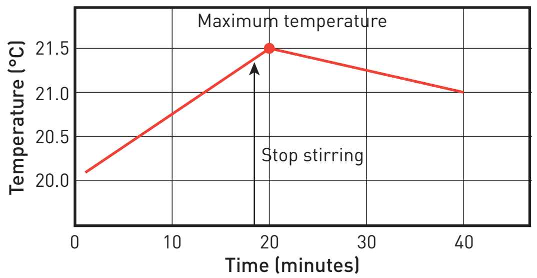
★★★ **21 Analyse** the construction of double-glazed windows to determine how they conserve energy.

Investigate, evaluate and communicate

★ **22 Propose** a reason for whether cork or iron allows heat to flow better.

★ **23** A 2 m × 1 m glass window is 4 mm thick and the temperature difference between the two sides is 20°C. **Devise** two means of slowing down the rate of heat flow through the window.

★★ **24** Students carried out Joule's experiment in the laboratory using 2.00 kg of water. They stopped stirring after 19 minutes. Figure 3 shows a graph of their results.



- **a Determine** the energy change in the water.
- **b** The mechanical work done on the water by the falling weights was 14 990 J. **Calculate** the percentage efficiency of the energy conversion process from mechanical to thermal energy.
- **c Discuss** possible sources of error in the experiment and their relative importance (qualitative).
- **d Propose** a reason why the water temperature kept increasing after the stirring stopped.
- **e Propose** a reason for the cooling of the water after 20 minutes.
- **f Propose** how this experiment could be improved.

★★ **25 Propose** a reason why many people die in intense bushfires without being touched by the flames.

★★ **26 Predict** and **justify** whether electric heaters can be used in outer space to keep astronauts warm.

★★ **27 a Propose** a reason why the thermometers used in weather stations are shielded from sunshine.

- **b Decide** what a thermometer measures if it is shielded from sunshine.
- **c Deduce** what a thermometer measures if it is **NOT** shielded from sunshine.

★★ **28 Assess** whether you can cool down your house in summer by leaving the refrigerator door open.

★★ **29** Car engines convert only about 20% of the energy in petrol to moving along the road. **Propose** a reason why the government can't pass a law that all the energy taken in by a car engine has to be used up.

★★★ **30** **Assess** the physics behind why people can dip their moist fingers in molten lead (400°C) without getting burnt. **Propose** how can this be. Do not try it!

★★★ **31** **Determine** the change in internal energy of a system that does 4×10^5 J of work while 3.00×10^6 J of heat transfer occurs into the system, and 3.4×10^6 J of heat transfer occurs to the environment.

★★★ **32** **Determine** which (if any) of the energy transfer diagrams in Figure 4 is not possible. Explain why.

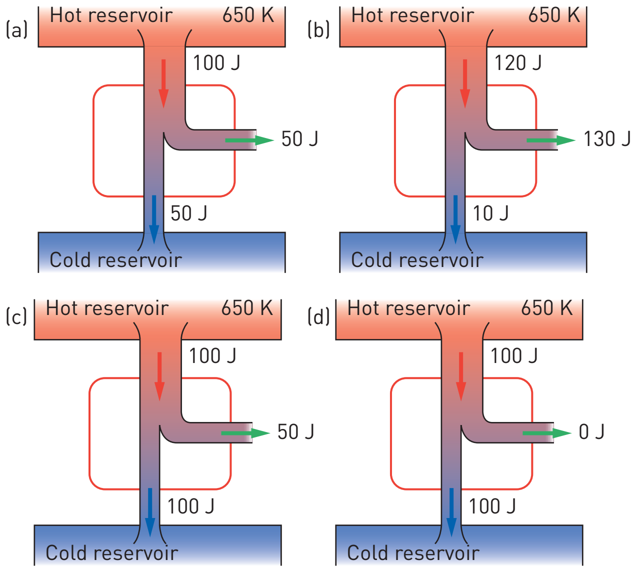


FIGURE 4 Four energy transfer diagrams

★★★ **33** A student's investigation into thermal efficiency involved heating water in a microwave oven and comparing the electrical energy input to the heat energy output. The student reported energy input as 227 700 J and heated up 1.0 L of water in a plastic ice cream bucket from 26.3°C to 54.3°C.

a **Calculate** the energy efficiency of the microwave oven.

b **Propose** some of the places the heat may have gone to make the efficiency less than 100%.

★★★ **34** **Evaluate** this statement: 'If useable energy is reduced every time an energy transfer occurs, we will eventually have no useable energy in the future.'

Check your obook assess for these additional resources and more:

» Student book questions
Chapter 3 revision questions

» Revision notes
Chapter 3

» assess quiz
Auto-correcting multiple choice quiz

» Flashcard glossary
Chapter 3

CHAPTER 4

Nuclear model and stability

Most people believe that atoms exist, but their incredibly small size is hard to comprehend. Only recently have scientists been able to see and photograph individual atoms.

Every breath you take contains about 10^{24} atoms. The full stop at the end of this sentence is a million atoms wide. Most people get very confused about atoms. Scientists have offered a model of the atom and nucleus that answers many of our questions.

OBJECTIVES

→ Describe the nuclear model of the atom characterised by a small nucleus surrounded by electrons.
→ Explain why protons in the nucleus repel each other.
→ Define the strong nuclear force.
→ Explain the stability of a nuclide in terms of the operation of the strong nuclear force over very short distances, electrostatic repulsion, and the relative number of protons and neutrons in the nucleus.

Source: *Physics 2019 v1.2 General Senior Syllabus Queensland Curriculum & Assessment Authority*

FIGURE 1 3D model of an atom, showing protons, neutrons and electrons

MAKES YOU WONDER

In this chapter, we will be examining some aspects of atoms that will help to answer questions such as:

→ If atoms are mostly empty space, why does a brick feel so hard?

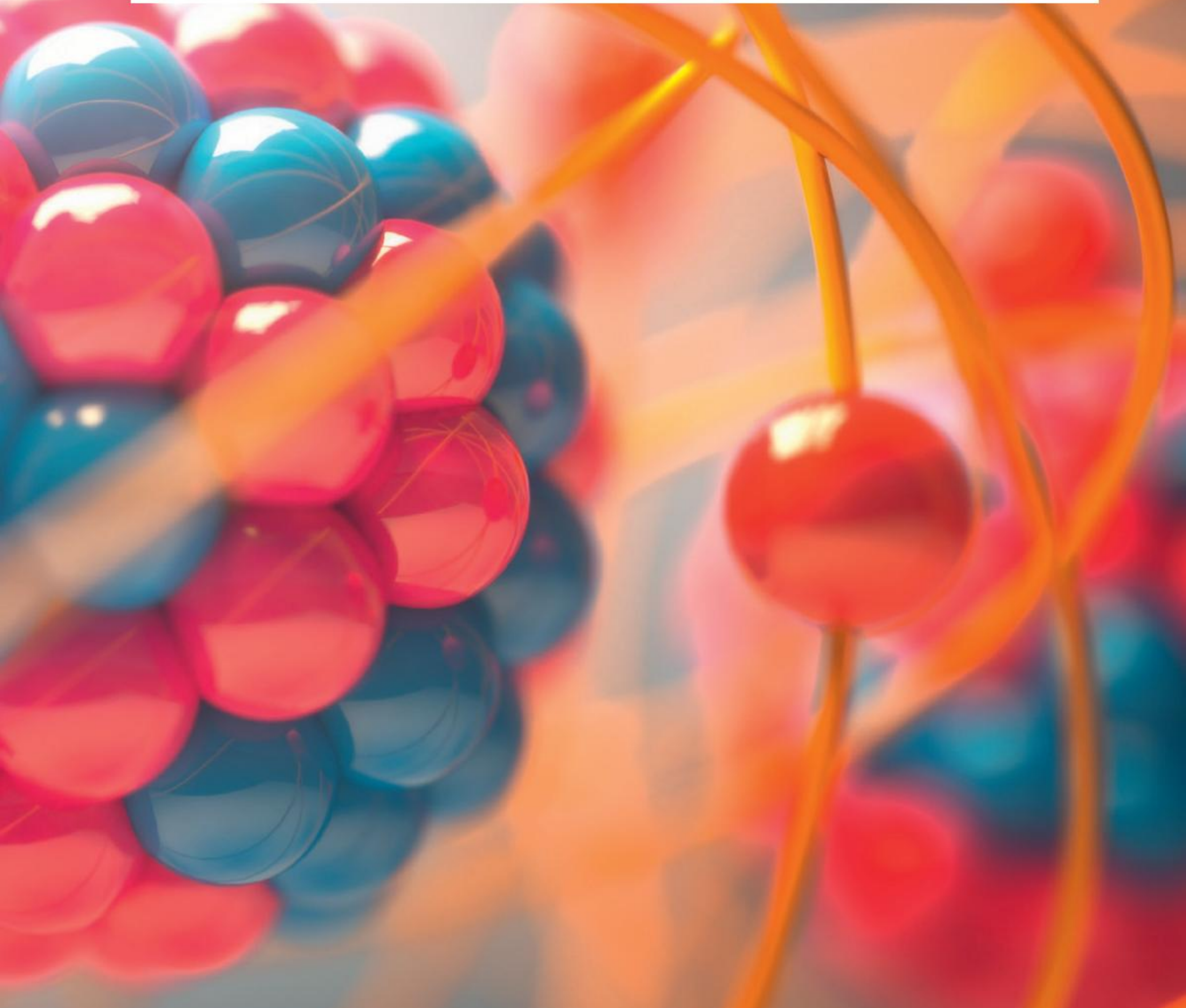
→ What colour is an atom?

→ If an electron has a negative charge, why doesn't it get sucked into the positively charged nucleus?

→ How many atoms are there in the universe? It must be a mind-bogglingly big number!

→ If the nucleus is made up of positive particles, why don't they repel each other and fly apart?

→ How do we know atoms really exist if we can't see them?



4.1 Nuclear model of the atom

KEY IDEAS

In this section, you will learn about:

+ the nuclear model of the atom
+ the characteristics of an atom
+ isotopes
+ atomic weight and mass.

Atoms are often referred to as the building blocks of matter because everything is made up of atoms.

Nuclear model

The atom is a part of the nuclear model of matter, where matter refers to a physical substance – anything that has mass and occupies space. An atom is the basic unit of matter and consists of a central, positively charged **nucleus** made up of **protons** and **neutrons** surrounded by a negatively charged cloud of **electrons**. These electrons are kept in orbit by electrostatic forces between the positive and negative charges.

About 99% of an atom's mass is concentrated in the nucleus. If you had a nucleus the size of a strawberry, it would be so heavy that it would bore its way through the ground. In Unit 4 you will see that protons and neutrons have an internal structure – they are made up of **elementary particles** called quarks. Particles with an internal structure are not considered to be elementary. Elementary particles are particles whose substructure is unknown.

nucleus
the positively charged central core of an atom, consisting of protons and neutrons and containing nearly all its mass

proton
a subatomic particle of about the same mass as a neutron with a +1 elementary electric charge, present in all atomic nuclei

neutron
a subatomic particle of about the same mass as a proton but without an electric charge, present in all atomic nuclei except those of ordinary hydrogen

electron
a subatomic particle of mass 1836 times lighter than a proton with a −1 elementary electric charge, present in all atoms

elementary particle
a particle whose substructure is unknown; for example, an electron or quark

FIGURE 1 The atoms in this lead fishing sinker will be around for billions of years. Lead atoms are generally very stable and last a very long time; however, there are some isotopes of lead that last for just fractions of a second.

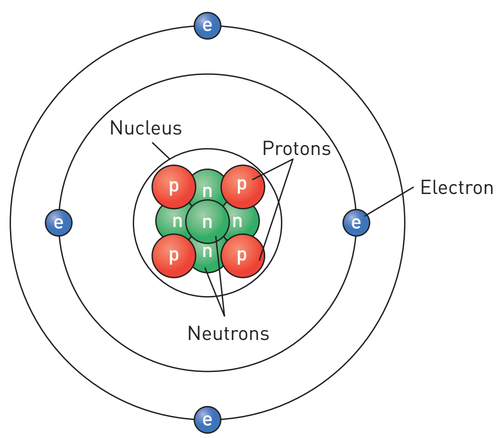


FIGURE 2 The nuclear model of the atom. The electrons are in a cloud surrounding the nucleus. The diagram is not intended to show the electrons as being in circular orbits, but rather in shells of different energy levels.

Characteristics of an atom

Chemical characteristics

The number of protons in an atom determines its name. Hydrogen has 1 proton, helium has 2, uranium has 92 and so on. The periodic table in the appendix (p. 492) shows this clearly. The number of protons is called the atom's **atomic number**, which has the symbol *Z*. Particles residing in the nucleus (protons and neutrons) are called **nucleons**. The different types of nuclei are referred to as **nuclides**; for example, there is a hydrogen nuclide, a helium nuclide and so on.

atomic number
the number of protons in an element's nucleus, Z

nucleons
protons or neutrons found in the nucleus of an atom

nuclides
a distinct kind of atom or nucleus characterised by a specific number of protons and neutrons

Mass and size

A proton or neutron has a mass 1836 times that of the electron. In a hydrogen atom, for example, nearly all of the mass is contained in the nucleus. However, the nucleus occupies only a tiny volume – about 1 trillionth (10^{-12}) the volume of the atom. If the nucleus were an orange seed, the main part of the electron cloud would be 100 m away. How big would the electron be? The electron is considered to be a point charge, so is not considered to have any size at all. Table 1 shows the masses and charges of some atomic particles. We can refer to the charge as elementary charges of +1 or –1.

TABLE 1 The mass and charge of atomic particles

Particle	Mass (kg)	Elementary charge
Proton	$1.6726219 \times 10^{-27}$	+1
Neutron	1.674925×10^{-27}	0
Electron	$9.1093835 \times 10^{-31}$	–1

Study tip

Atom diagrams are commonly drawn as shown in Figure 3, but these diagrams can sometimes be a bit misleading. Try to think of electrons in shells of energy levels rather than following a circular path around the nucleus.

The simplest atom is that of hydrogen (Greek *hydro* = 'water', *genes* = 'to form', that is, you can form water by burning it). It has 1 proton and 0 neutrons, so its atomic number *Z* (number of protons) is 1 and its mass number *A* (the sum of protons and neutrons, or p + n) is also 1.

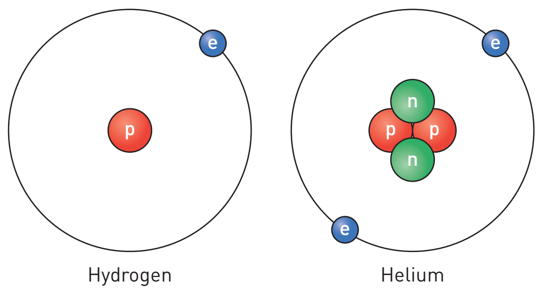


FIGURE 3 Hydrogen and helium atom models

We can continue to add protons to our model, and at the same time add more electrons and neutrons (Figure 3). After helium (2 protons) is lithium with 3 protons, beryllium with 4 protons and so on. The number of protons determines the name of the atom; for example, all atoms with 8 protons are called oxygen, and oxygen always has 8 protons. People often ask, 'What would happen if oxygen had 7 protons?' The answer is it wouldn't be oxygen, it would be nitrogen.

Let's consider the number of electrons in the electron cloud of an atom. Electrons have a negative charge of –1, and protons (in the nucleus) have a charge of +1. If the number of positive charges and the number of negative charges is equal, the atom is said to be neutral (from the Latin word meaning 'neither one nor the other'). If the atom has more positive than negative charges, the atom is positive overall. Chemists call it a positive ion. If it has more negative than positive charges, it is a negative ion.

Study tip

When discussing atoms, protons, neutrons and electrons are often shortened to p, n and e respectively. Be careful answering questions: the variable *n* (in italics) usually means 'number', so make sure your read the information in exam questions carefully.

TABLE 2 The overall charge of oxygen can vary with the number of electrons.

Atom	Number of protons (+1 charge on each)	Number of electrons (–1 charge on each)	Overall charge	Symbol
Oxygen	8	8	0	O
Oxygen	8	9	–1	O^-
Oxygen	8	10	–2	O^{2-}
Oxygen	8	7	+1	O^+

For example, oxygen has 8 protons, so the nucleus has an +8 charge. If oxygen has 8 electrons (–8), it is then a neutral atom (O). If oxygen has more electrons (such as 10), it is a negative ion (O^{2-}). With fewer electrons (such as 7), it will be a positive ion (O^{+}).

Isotopes

isotope
a form of an element with the same number of protons but different number of neutrons

Historically, when scientists were discovering more and more elements, they were struggling to fit them onto the existing structure of the periodic table. This was especially so for the radioactive elements – those between lead (atomic number $Z = 82$) and uranium ($Z = 92$). Cases began to appear in which two radioactive elements, distinctly different in the type of radiation they emitted, were otherwise chemically identical. In 1913, Frederick Soddy found that there were two forms of lead – one was the ordinary sort with a mass number of 207 units, and the other (taken from a uranium deposit in Norway) had a mass of 206 units. Soddy concluded that such inseparable elements must occupy the same place in the periodic table and gave them the name **isotopes** (Greek *iso* = 'same', *topos* = 'place').

Isotopes of an element have the same number of protons but different numbers of neutrons. In the previous lead example, both isotopes have 82 protons, but one has 124 neutrons (206 – 82) and the other has 125 neutrons (207 – 82).

The chemical properties of isotopes are identical, but the physical properties are different because of the different masses.

Figure 4 shows the three isotopes of hydrogen – hydrogen (H), deuterium (D) and tritium (T). Their composition is shown in Table 3. Water (H_2O) made with ordinary hydrogen ^1_1H has a density of 1.000 g cm^{-3} and boils at 100.00°C, whereas 'heavy water' made from deuterium oxide (D_2O) has a density of 1.1079 g cm^{-3} and a boiling point of 101.42°C.

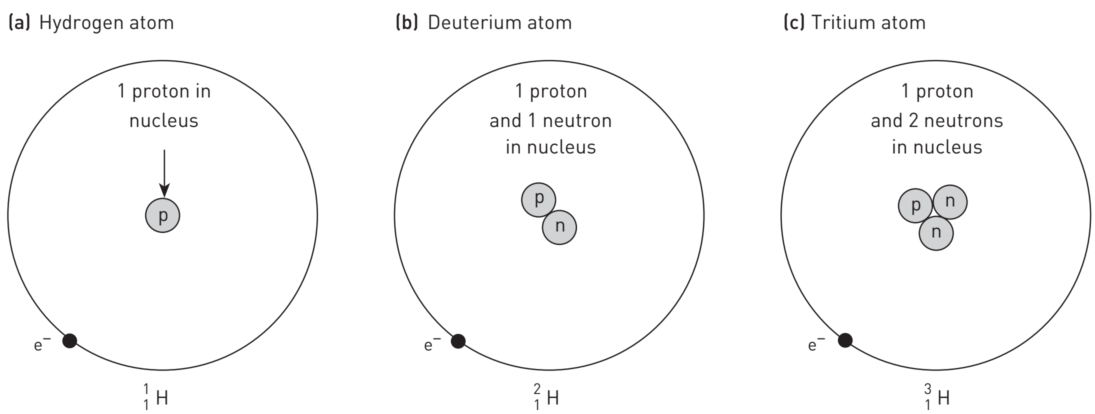


FIGURE 4 The three isotopes of hydrogen – the most plentiful is ^1_1H (a).

TABLE 3 The isotopes of hydrogen

Isotope (nuclide)	Symbol	Protons (atomic number)	Neutrons	Protons + neutrons (mass number)	Electrons
Hydrogen	^1_1H	1	0	1	1
Deuterium	^2_1H	1	1	2	1
Tritium	^3_1H	1	2	3	1

The element with the most isotopes is gold. It has 30 isotopes with mass numbers ranging from 175 to 204. The only stable gold isotope is $^{197}_{97}Au$, from which gold jewellery is made. The other 29 are radioactive.

Each isotope is referred to as a nuclide. Figure 5 shows the shorthand way of describing a nuclide. For example, the isotopes of hydrogen are written as ${}^{1}_{1}H$, ${}^{2}_{1}H$ and ${}^{3}_{1}H$.

The lead isotopes mentioned earlier would be written as ${}^{206}_{82}Pb$ and ${}^{207}_{82}Pb$, but could also be written as Pb-206 and Pb-207. All isotopes of lead have an atomic number of 82 and all atoms with an atomic number of 82 are lead. There can be other nuclides with a mass number of 206 besides lead (for example, ${}^{206}_{83}Bi$ or ${}^{206}_{84}Po$).

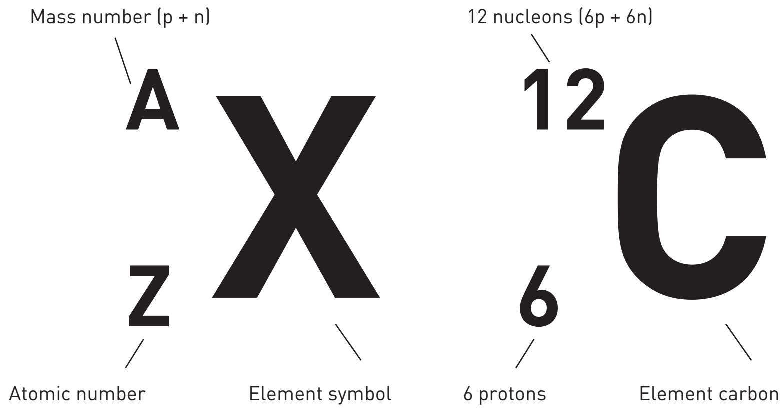


FIGURE 5 Nuclide nomenclature

Study tip

The symbol and the atomic mass of isotopes can be found by consulting the periodic table shown in Appendix 2.

Study tip

Students often get confused when trying to work out the (letter) symbols for nuclides. Remember that the atomic number Z (the number of protons) and the letter symbol go hand-in-hand: 82 protons means Pb, and Pb means 82 protons.

Study tip

The term 'relative atomic mass' now seems to be gaining as the preferred term over 'atomic weight', but there is no real agreement.

CHALLENGE 4.1A

Isobaric substances

Atoms of substances with different atomic numbers but the same mass number are said to be isobaric (Greek *iso* = 'the same', *baros* = 'weight'). An example is ${}^{239}_{92}U$ and ${}^{239}_{93}Np$. Find another two isobaric substances and list their numbers of protons, neutrons and electrons.

Atomic mass units

The masses of neutrons, protons and electrons have been accurately measured (using a mass spectrometer). The masses are expressed as 'unified atomic mass units', which are referred to as amu or just u. The unified atomic mass unit is equal to one-twelfth of the mass of a ${}^{12}C$ atom. The unified mass unit includes the masses of the six electrons of the carbon atom. A unified atomic mass unit (u) is a unit of mass used for very small masses and is equal to 1.66×10^{-27} kg.

The masses of atomic particles are as follows (where $1\ u = 1.6606 \times 10^{-27}$ kg):

- proton (m_p) = 1.007 276 u
- neutron (m_n) = 1.008 665 u
- electron (m_e) = 0.000 549 u

Atomic weight and mass number

The 'atomic weight' of an element is the average mass of the atoms of an element as it is found in nature. Atomic weight is more useful in chemistry than in physics, but should be clarified here. Since most elements exist as isotopes, atomic weight is really an average of the masses of the isotopes present.

For example, on Earth, ordinary carbon consists of 98.89% ${}^{12}C$, 1.11% ${}^{13}C$ and a trace of (1×10^{-8} %) ${}^{14}C$. The average atomic weight is 98.89% of ${}^{12}C$ plus 1.11% of ${}^{13}C$, which equals 12.0111 units. This is called the **relative atomic mass** (A_r) or **atomic weight** of carbon, both of which refer to averages. Only ${}^{12}C$ (the most abundant) has a relative atomic mass of exactly 12.0000.

relative atomic mass
the ratio of the average mass of atoms of an element (in a given sample) to one unified atomic mass unit

atomic weight
an older alternative term for relative atomic mass

Most elements exist as a number of isotopes. Uranium contains three isotopes of atomic mass 234, 235 and 238. Table 4 shows the particle composition of these isotopes. Note that the mass number is a whole number (being the number of protons), whereas exact mass shows the mass correct to 6 decimal places. The exact mass of other nuclides to 6 decimal places is in Appendix 1.

TABLE 4 The isotopes of uranium and their masses, including orbiting electrons

Isotope	Atomic number	Proton number	Electron number	Neutron number	Mass number	Exact mass (u)
	(Z)	(Z)	(Z)	($A - Z$)	(A)	
^{234}U	92	92	92	142	234	234.040 952
^{235}U	92	92	92	143	235	235.043 930
^{238}U	92	92	92	146	238	238.050 788

CHALLENGE 4.1B

Helium nucleus

The radius of a helium nucleus (^4He) is 1.9×10^{-15} m.

a Calculate its volume using $V = \frac{4}{3}\pi r^3$.

The mass of a helium nucleus (excluding electrons) is 4.001 505 u.

b Calculate its mass in kilograms.

c Calculate the density of the nucleus using $D = \frac{m}{V}$.

FIGURE 6 Atoms are often referred to as the building blocks of matter.

CHECK YOUR LEARNING 4.1

Describe and explain

1 **Describe** the structure of an atom.

2 **Explain** in your own words what an isotope is.

Apply, analyse and interpret

Refer to the periodic table to answer the following questions.

3 **Determine** the symbols of the two common isotopes of carbon with atomic masses 12 and 14.

4 **Determine** the number of protons and neutrons in each of the nuclides represented by:

a $^{2}_{1}H$
b $^{12}_{6}C$
c $^{17}_{8}O$
d $^{23}_{11}Na$
e $^{32}_{16}S$
f $^{107}_{47}Ag$
g $^{127}_{53}I$
h $^{238}_{92}U$

5 **Determine** the missing values from Table 5 to show the composition of each nuclide.

Investigate, evaluate and communicate

6 **Consider** the nuclide $^{239}_{92}U$.

a **Determine** how many neutrons, protons and nucleons there are in it.

b **Predict**, if one extra nucleon could be added, what the possible formulas are for it (in the $^{A}_{Z}X$ pattern).

c **Deduce** which one of the formulas, in your answer to part b, is an isotope of the original. Explain your answer.

7 The isotope ^{238}U occurs in most rocks on Earth in concentrations of about 3 parts per million (0.0003%). It is as common as tin, and about 40 times as common as silver. Most ^{238}U on Earth was formed in a supernova about 6.6 billion years ago and arrived on Earth about 4 billion years ago.

a **Construct** a timeline (poster) showing five stages in the life of a ^{238}U atom from its birth in the supernova, to its journey through the heavens and arrival, life and death on Earth.

b **Propose** evidence for each stage and make clear any alternative timelines by showing what may have happened to its brother and sister ^{238}U atoms it was created with. For any statements that could be contradicted, you should rebut with further evidence.

TABLE 5

Symbol ($^{A}_{Z}X$)	Symbol	Number of protons	Number of neutrons	Number of nucleons (protons + neutrons)	*A*	*Z*
$^{64}_{29}Cu$	Cu-64					
	P-32					
		38	50			
			124			82
	Ra-?			220		
					239	93
$^{239}_{92}?$						

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Nuclear model of the atom

4.2 Mass defect and binding energy

KEY IDEAS

In this section, you will learn about:

- mass defect and its formula
- the binding energy of a nucleus
- the conversion between different energy units.

When accurate measurements of the masses of nucleons and nuclei are made, a significant discrepancy emerges. The mass of a nucleus is always less than the combined individual masses of its component nucleons.

mass defect
the difference between the mass of a nucleus and the sum of the component parts (symbol: Δm)

For example, the mass of a deuterium nucleus ${}^{2}_{1}H$ is 2.013 553 u, but the sum of the masses of the individual proton and neutron is 2.015 941 u. The difference in mass (0.002 388 u) is called the **mass defect** (Δm). 'Defect' means something is missing, so you need to think of the relationship the other way around. If you made a nucleus from component particles, it would be lighter than the particles making it up. It would appear that some mass has 'disappeared', so it is called a defect.

$$\text{mass of nucleus} < \text{mass of constituent particles}$$

$$m_{nucleus} < m_{cp}$$

$$2.013\,553 \text{ u} < 2.015\,941 \text{ u}$$

$$\text{mass defect } (\Delta m) = m_{cp} - m_{nucleus}$$

$$= 2.015\,941 \text{ u} - 2.013\,553 \text{ u}$$

$$= 0.002\,388 \text{ u}$$

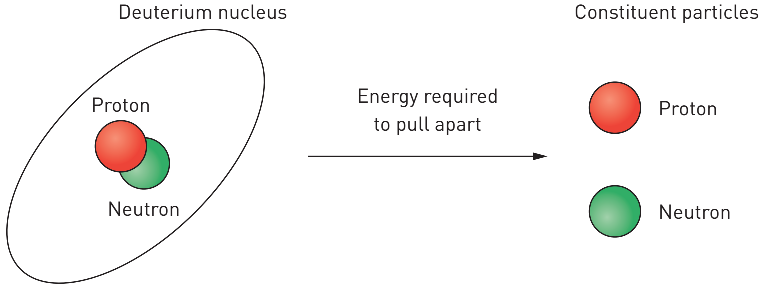

FIGURE 1 Pulling apart a nucleus requires energy, which appears as mass in the products.

It is very difficult for scientists to measure the mass of the nucleus of an atom. It is much easier to measure the mass of the whole atom, including electrons. These masses appear in Appendix 1. When calculating binding energies of atoms, you will have to include the mass of the electrons in the component particles.

Binding energy

A ${}^{12}C$ atom is made up of 6 protons, 6 neutrons and 6 electrons. The masses and the sum of these masses is as follows:

6 protons:	6 × 1.007 276 u = 6.043 656 u
6 neutrons:	6 × 1.008 665 u = 6.051 990 u
6 electrons:	6 × 0.000 549 u = 0.003 294 u
Total mass:	= 12.098 940 u

However, the exact mass of a ${}^{12}_{6}C$ nuclide (including its 6 electrons) is 12.000 000 u, which is less than the sum of its component particles. Where has the missing 0.098 940 u gone? Has it disappeared into thin air? The loss of mass was defined by scientist F. W. Aston as mass defect (Δm), and it represents the mass that has been converted to **binding energy** – energy that binds or holds the nuclear particles together.

binding energy the energy needed to overcome the forces holding a nucleus together to disassemble it into component parts

In general, binding energy represents the mechanical work that must be done against the forces holding a nucleus together to disassemble it into component parts. When you pull a carbon nuclide apart, it requires energy. The energy that goes into the particles gets converted to a mass of 0.098 94 u.

$$\begin{aligned}\text{Mass defect } (\Delta m) &= m_{cp} - m_{nuclide}\\ &= 12.098\,940 \text{ u} - 12.000\,000 \text{ u}\\ &= 0.098\,940 \text{ u}\end{aligned}$$

We can put this another way:

Nuclide (low mass) + binding energy (mass defect) = component particles (higher mass)
12.000 000 u + 0.098 940 u = 12.098 940 u

Mass defect (Δm) is the difference in mass between the nuclide and the sum of its component particles. It represents the mass that has been converted to binding energy.

$$\Delta m = m_{cp} - m_{nuclide}$$

Binding energy represents the mechanical work that must be done against the forces holding a nucleus together to disassemble it into component parts.

Energy in joules

You will be familiar with expressing energy in joules, so we need to convert this binding energy to joules. Einstein showed that mass and energy are equivalent, and one can be converted into the other. Using his equation showing the relationship between mass and energy $E = mc^2$, we can calculate the amount of energy involved. This is sometimes written as

$$\Delta E = \Delta m c^2$$

to make it clear that we are talking about the **change in energy** associated with the **change in mass**. The constant of proportionality is c^2 where c is the speed of light in a vacuum (3×10^8 m s^{-1}).

Firstly, we have to convert the mass defect in atomic mass units (u) to mass defect in kilograms (kg): 1 u = 1.66×10^{-27} kg.

Mass defect of ^{12}C:

$$\Delta m = 0.098\,940 \text{ u}$$

Convert u to kg:

$$\begin{aligned}\Delta m &= 0.098\,940 \text{ u} \times 1.6606 \times \frac{10^{-27} \text{ kg}}{\text{u}}\\ &= 1.643 \times 10^{-28} \text{ kg}\end{aligned}$$

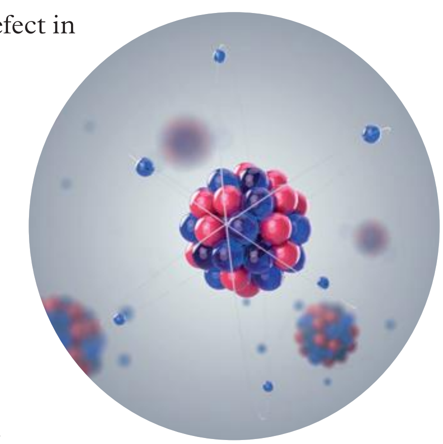

FIGURE 2 Binding energy is the energy required to separate this nucleus into separate neutrons (blue) and protons (red).

Then we can calculate the binding energy in J by a simple conversion using Einstein's famous formula $E = mc^2$. In this equation, m is the mass defect in kilograms, c is the speed of light (3×10^8 m s^{-1}), and E is the equivalent energy in joules. So, for a mass defect of 1.643×10^{-28} kg:

$$\begin{aligned}E &= mc^2\\ &= 1.643 \times 10^{-28} \text{ kg} \times (3 \times 10^8)^2\\ &= 1.48 \times 10^{-11} \text{ J}\end{aligned}$$

Physicists also like to express the binding energy as J per nucleon. In the case of carbon, there are 12 nucleons (6p + 6n), so the binding energy of 1.48×10^{-11} J is divided by 12 to give 1.23×10^{-12} J/nucleon.

$$\begin{aligned}\text{Binding energy per nucleon} &= \frac{\text{binding energy}}{\text{number of nucleons}}\\ &= \frac{1.48 \times 10^{-11}\ \text{J}}{12}\\ &= 1.23 \times 10^{-12}\ \text{J/nucleon}\end{aligned}$$

Energy in electron volts

electron volt (eV)
a unit of energy defined as the work done on an electron in moving it through an electrical potential difference of 1 volt

Another common unit for energy used by physicists is **electron volts** (eV). We could express binding energy in electron volts (eV) or megaelectron volts (MeV, that is, a million eV). MeV is an energy term used by physicists as a more convenient unit than joules.

Electron volt (eV) is a unit of energy equal to the work done on an electron in accelerating it through a region of space where there is a potential difference of one volt. One eV is equal to 1.6×10^{-19} J.

1 u of mass defect is equivalent to 931.5 MeV.

In the case of ^{12}C, a mass defect (Δm) of 0.098 940 u can be converted to MeV:

$$0.098\,940\ \text{u} \times \frac{931.5\ \text{MeV}}{\text{u}} = 92.16\ \text{MeV}$$

Recall that physicists also like to express binding energy per nucleon. In this case, it would be as MeV per nucleon. For ^{12}C, there are 12 nucleons (6p + 6n), so the binding energy of 92.16 MeV is for 12 nucleons, which means there is 92.16 ÷ 12 = 7.68 MeV per nucleon.

Conversion factors:

$$\begin{aligned}1\ \text{u} &= 1.66 \times 10^{-27}\ \text{kg}\\ &= 931.5\ \text{MeV}\\ 1\ \text{eV} &= 1.6 \times 10^{-19}\ \text{J}\end{aligned}$$

TABLE 1 Summary for $^{12}_{6}$C

Quantity	Symbol	Value
mass of component particles (u)	m_{cp}	12.098 940
observed mass from table (u)	$m_{nucleus}$	12.000 000
mass defect (u)	Δm	0.098 940
mass defect (kg)	Δm	1.643×10^{-28}
binding energy (J)	BE	1.48×10^{-11}
binding energy per nucleon (J)	BE/nucleon	1.23×10^{-12}
binding energy (MeV)	BE	92.16
binding energy per nucleon (MeV)	BE/nucleon	7.68

WORKED EXAMPLE 4.2

For the nuclide $^{4}_{2}$He, calculate:

a mass defect in u

b mass defect in kg

c binding energy in J

d binding energy in J/nucleon

e binding energy in MeV

f binding energy in MeV per nucleon.

SOLUTION

a Mass of $^{4}_{2}He$ (nucleus and electrons) from Appendix 1 = 4.002 603 u.

Components:

2p = 2 × 1.007 276 u = 2.014 552 u

2n = 2 × 1.008 665 u = 2.017 330 u

2e = 2 × 0.000 549 u = 0.001 098 u

Total = 4.032 980 u

Δm (mass defect) = 4.032980 − 4.002603
= 0.030 377 u

b Δm (mass defect) in kg $= 0.030\,377 \text{ u} \times \frac{1.6606 \times 10^{-27} \text{ kg}}{\text{u}}$

$= 5.044 \times 10^{-29}$ kg

c Binding energy (in J) $= \Delta m c^2$

$= 5.044 \times 10^{-29} \text{ kg} \times (3 \times 10^8)^2$

$= 4.540 \times 10^{-12}$ J

d Binding energy (in J/nucleon) $= \frac{\text{BE}}{\text{mass number}}$

$= \frac{4.540 \times 10^{-12} \text{ J}}{4}$

$= 1.135 \times 10^{-12}$ J/nucleon

e Binding energy (in MeV) $= \Delta m(\text{u}) \times \frac{931.5 \text{ MeV}}{\text{u}}$

$= 0.030\,377 \text{ u} \times \frac{931.5 \text{ MeV}}{\text{u}}$

= 28.3 MeV

Alternatively:

Binding energy(eV) $= \frac{\text{Binding energy(J)}}{1.6 \times 10^{-19} \text{ J/eV}}$

$= \frac{4.540 \times 10^{-12} \text{ J}}{1.6 \times 10^{-19} \text{ J/eV}}$

$= 2.83 \times 10^7$ eV

=28.3 MeV

f Binding energy(in MeV/nucleon) $= \frac{28.3 \text{ MeV}}{4}$

= 7.1 MeV/nucleon

Variation in binding energy

The more nucleons that are present in an atom's nucleus, the greater the forces holding the nucleus together and hence the greater the binding energy necessary to pull it apart. For example, ^{12}C has a binding energy of 92.16 MeV, whereas ^{235}U is 1783.9 MeV. However, expressing the required energy as the binding energy per nucleon gives a measure of how **stable** the nucleus is. The greater the binding energy per nucleon, the more stable it is and the harder it is to rip it apart into its component particles.

stable
characteristic of nuclides that are not radioactive and so (unlike radionuclides) do not spontaneously undergo radioactive decay.

Let's compare the stability of the nuclides ^{12}C and ^{235}U:

$$^{12}\text{C has a binding energy of } \frac{92.16 \text{ MeV}}{12} = 7.68 \text{ MeV/nucleon.}$$

^{235}U has a binding energy of 1783.9 MeV but has 235 nucleons: $\frac{1783.9}{235}$ = 7.59 MeV per nucleon.

Therefore, the carbon nucleus is more stable.

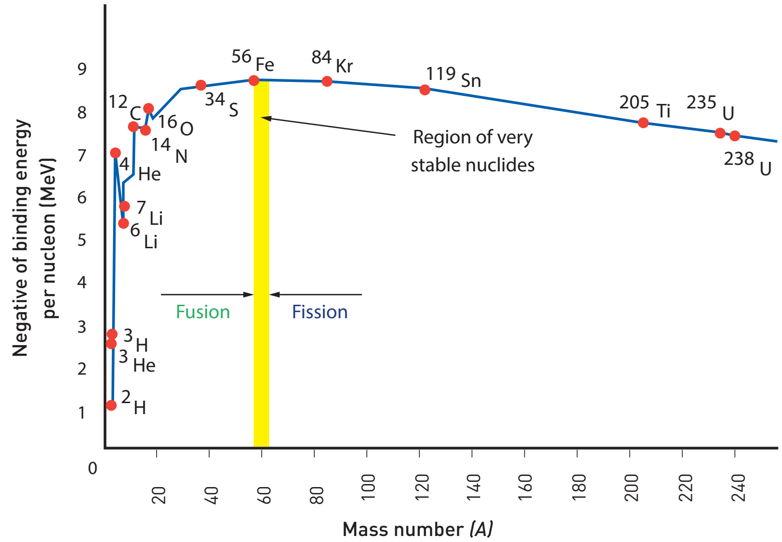

FIGURE 3 Variation in binding energy per nucleon

If we plot a graph of the binding energy per nucleon against the mass number (Figure 3), we can see the most stable nuclides are those with the highest binding energy per nucleon: mass numbers around 50–60 u (for example, ^{56}Fe at a value of 8.8 MeV/nucleon). Heavy nuclides with mass numbers to the right of this region are most likely to undergo nuclear fission and break into smaller nuclides to become more stable. Light nuclei to the left of this region are more likely to undergo nuclear fusion and join together to form heavier nuclides. Fission and fusion reactions will be covered in Chapter 5.

CHECK YOUR LEARNING 4.2

Describe and explain

1 **Define** mass defect.

2 **Explain** in your own words the meaning of binding energy.

3 **Explain** how a nucleus can have less mass than its components when, in comparison, a brick house has the same mass as the components that make it up.

Apply, analyse and interpret

4 **Interpret** data in the table of exact nuclide masses in Appendix 1 to **calculate** the binding energy of the following in

- i MeV
- ii MeV per nucleon
- iii joules
- iv J/nucleon

- a tritium atom $^{3}_{1}H$
- b He-3
- c N-14
- d O-16.

5 **Calculate** the binding energy per nucleon for $^{56}_{26}Fe$ and **compare** it with the approximate value of 8.8 MeV/nucleon obtained from the graph in Figure 3. Note that $^{56}_{26}Fe$ is among the most tightly bound (stable) of all nuclides. It has even numbers of both protons and neutrons, and its mass is 55.934 936 u.

OC

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- Increase your knowledge
  Mass defect
- » Weblink
  Binding energy
- » Weblink
  Mass defect

4.3 Nuclear stability

KEY IDEAS

In this section, you will learn about:

- the operation of strong nuclear force over very short distances
- electrostatic repulsion
- the relative number of protons and neutrons in the nucleus.

nuclear stability
a measure of the stability of an isotope determined from the neutron/proton ratio and the total number of nucleons in the nucleus

radioactive
describes substances which have nuclei with an excess of energy and spontaneously emit radiation to reduce excess energy

An important part of the senior physics course is being able to understand and describe **nuclear stability**. In Section 4.2 we learnt that the greater the binding energy per nucleon, the more stable it is. But that's not all there is to nuclear stability. If a nuclide is stable, it is not considered **radioactive** and will not decay. If a nuclide is not stable, it is considered radioactive and will emit particles from the nucleus. So, what makes a nuclide stable?

Case study 4.3

Transmutations and nuclear stability

For centuries, medieval researchers sought in vain for a material that could turn ordinary metals such as lead into the precious metal gold – a process they called transmutation (Latin *trans* = 'across', *mutare* = 'change'). These people called themselves alchemists (Greek *chyma* = 'to fuse a metal'). Alchemists developed numerous techniques that are still used in laboratories today, such as distillation, crystallisation, sublimation and fusion. They derived many useful materials in the process, such as caustic soda, red lead, tin oxide and various alloys. These substances we call materials because they have particular qualities or are used for specific purposes.

Alchemists used many substances not commonly found in laboratories today: hair, skull, brains, bile, blood, milk, urine and horn. No wonder they didn't turn lead into gold! But it wasn't the chemicals that caused them to fail – it was their underlying theory of matter.

The alchemists believed in Aristotle's four-element theory (earth, wind, fire and water). Until this was overthrown, science couldn't progress. Little did they know that, in nature, many atoms transmute from one form to another in the normal course of events. When atoms transmute, they are said to be radioactive and particles are emitted by the nucleus. These particles can be alpha particles, beta particles or a neutron. In many cases, a gamma ray is also emitted. The question that bothered physicists was why some nuclei were radioactive (such as uranium) and why some were stable (such as lead) and stayed unchanged indefinitely. The answer lies in the way the nucleus is structured.

Electrostatic repulsion

electrostatic repulsion
the phenomenon of two like charged particles repelling each other

The nucleus is made up of protons and neutrons. The protons are positively charged and, because they are almost touching, the force of the **electrostatic repulsion** is enormous.

But why don't the protons fly apart? The answer lies in the role of the neutrons.

Strong nuclear force

strong nuclear force
force that acts over very small distances in the nucleus to hold the nucleons together against the repulsive electrostatic forces between the positively charged protons. It is one of the four fundamental forces

fundamental forces
the four forces that are mediated by one or more particles. They are, in order from strongest to weakest: the strong nuclear, the electromagnetic, the weak nuclear and the gravitational force

Neutrons serve two purposes – to add some distance between the protons to reduce the repulsive force, and to act as a nuclear 'glue'. This gluing force is called the strong force or **strong nuclear force**. As the number of protons increases, the number of neutrons must also increase. This strong force is an attractive force that binds adjacent nucleons together. It is a very short-range force because, unlike the electrostatic force that decreases as the inverse square of the distance, the strong force decreases rapidly as separation increases, but at very close separations it becomes repulsive (Figure 1). If it wasn't repulsive at close distances, the particles would merge and collapse to a point.

There are four **fundamental forces** that act between bodies of matter and that are mediated by one or more particles. In order from strongest to weakest they are: the strong nuclear force, the electromagnetic force, the weak nuclear force and the gravitational force.

The strong nuclear force is a fundamental force that acts over small distances in the nucleus to hold the nucleons together against the repulsive electrostatic (electromagnetic) forces exerted between the protons.

Note that the strong nuclear force acts between all nucleons no matter if they are protons or neutrons. Their charge has nothing to do with it. However, when nucleons are just a few diameters apart, the strong nuclear force is nearly zero.

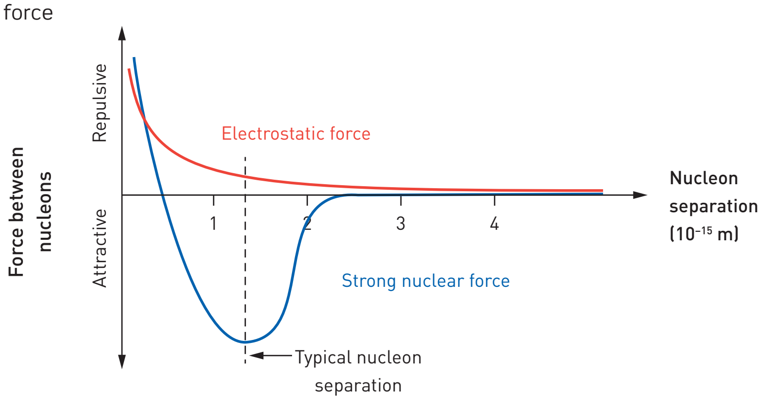

FIGURE 1 As the diameter of the nucleus increases (horizontal axis), the attractive strong nuclear force reduces to almost zero and all that remains is the repulsive electrostatic force.

For the smaller nuclei, the number of neutrons required for stability is about the same as the number of protons present (that is, an n/p ratio of 1:1). For example, the most stable isotope of oxygen is $^{16}_{8}O$. It has 8 protons and 8 neutrons. Similarly, ordinary carbon is $^{12}_{6}C$ (6p, 6n). However, as the number of protons increases, the strong (attractive) force becomes much less and it is the electrostatic (repulsive) force that dominates. So, the number of neutrons required for stability increases– the n/p ratio becomes greater than 1:1 (around 1.5:1). Stable zinc is $^{64}_{30}Zn$, which has 30 protons and 34 neutrons, so the n/p ratio is 1.13.

Study tip

You need to be able to explain the stability of a nuclide in terms of the following:

- strong nuclear force acting over short distances only
- electrostatic repulsion needing to be overcome
- the number of protons and neutrons present.

Table 1 lists the neutron/proton ratio of some common stable nuclides. The more massive the atom, the greater the n/p ratio needs to be. Note that the n/p ratio starts at 1.00 and increases to 1.59 for uranium.

TABLE 1 Examples of nuclear force for some common stable nuclides

Stable nuclide	Protons (*Z*)	Neutrons (*N*)	n/p ratio
$^{16}_{8}O$	8	8	1.00
$^{64}_{30}Zn$	30	34	1.13
$^{207}_{82}Pb$	82	125	1.52
$^{238}_{92}U$	92	146	1.59

Figure 2 shows a graph of neutron number against proton number. The dots show stable nuclei and the region where they occur is often called the 'island of stability'. Outside this region, the nucleus undergoes natural radioactive decay and breaks apart because of the instability caused by the competing electrostatic force and the strong nuclear force.

In Figure 2, the black line at 45° shows where the ratio of neutrons to protons is 1:1 (or $Z = N$). The nuclides shown as black squares are the stable ones and the rest undergo various forms of decay. The column on the right shows how stable the nuclides are in terms of their half-life. The black squares have an effectively infinite half-life so are very stable. The nuclides in shades of blue last only a matter of seconds. There are no completely stable nuclides above a proton number (Z) of 82 (that is, an atomic number of 82). This is will be discussed more in the next chapter.

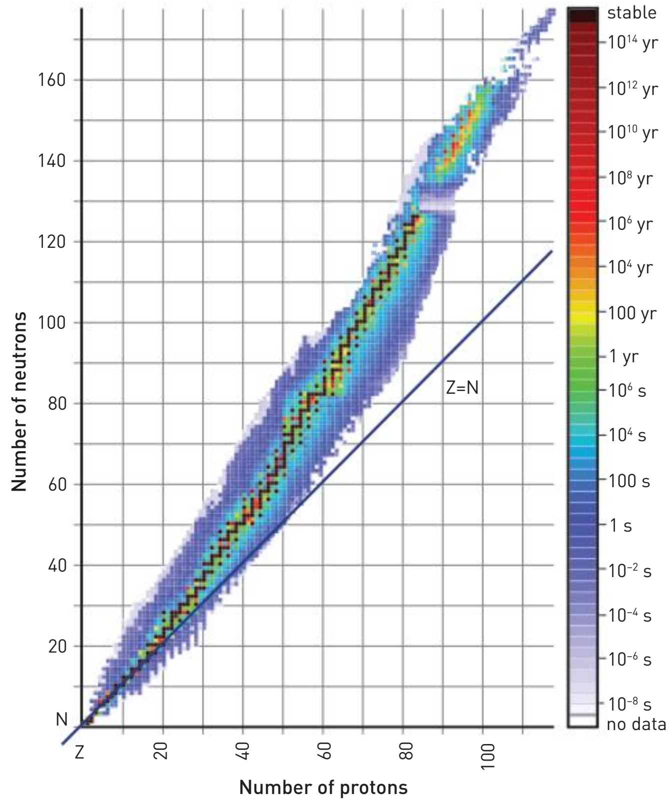

FIGURE 2 Graph of proton (or atomic) number (*Z*) versus the neutron number (*N*) for common isotopes. It is often called an n/p graph.

CHECK YOUR LEARNING 4.3

Describe and explain

1 **Explain** what is meant by nuclear stability.

2 **Describe** what happens to a nuclide that is unstable.

3 **Explain** how distance is relevant to the strong nuclear force.

Apply, analyse and interpret

Refer to the periodic table (Appendix 2) to answer the following questions.

4 **Interpret** the n/p graph in Figure 2 to **deduce** whether the following combinations are stable:

a $Z = 80, N = 85$

b $Z = 70, N = 95$

c $Z = 44, N = 90$

5 **Determine** whether this statement is true or false: 'Nuclides will be stable if $N>Z$.' Explain your thinking.

6 **Deduce** whether $^{90}_{30}Zn$ is stable and explain your reasoning.

Investigate, evaluate and communicate

7 **Predict** the composition of nuclide of calcium that is stable and write its formula in the $^{A}_{Z}X$ format.

8 **Evaluate** the possibility of there being more than one nuclide that has a mass number of 90 and is stable.

9 **Evaluate** this statement: 'If a nuclide has a n/p ratio of 1:1, it will not be stable'.

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» Weblink
Using nuclear energy

» Weblink
Nuclear forces

» Weblink
Strong nuclear force

SCIENCE AS A HUMAN ENDEAVOUR

4.4 Was the strong nuclear force invented or discovered?

KEY IDEAS

In this section, you will learn about:

+ the operation of the strong nuclear force over very short distances.

The development of models of the atom often required a wide range of evidence from multiple individuals and across disciplines.

Before the 1970s, physicists were uncertain as to how the atomic nucleus was bound together. It was known that the nucleus was composed of protons and neutrons, and that protons possessed positive electric charge while neutrons were electrically neutral. By the understanding of physics at that time, positive charges would repel one another and the positively charged protons should cause the nucleus to fly apart. However, this was never observed. New physics was needed to explain this phenomenon.

We now know about the strong nuclear force, which explains this. It is one of the four known fundamental interactions (the others being electromagnetism, the weak interaction and gravitation).

Was the concept of strong nuclear force discovered or was it invented? Many scientists are associated with the concept. The key moments in our understanding of strong nuclear force are outlined in Figure 1.

1919
Ernest Rutherford is credited with discovering the proton. He was able to deduce that electromagnetism should cause the protons in the nucleus to repel each other since they have a positive charge.

1932
James Chadwick discovered neutrons in the nucleus of atoms.

1933
Eugene Wigner suggested that two forces hold the nucleus together: the strong and the weak nuclear forces (rather than the electromagnetic force).

1935
Hideki Yukawa developed his first theory to explain the mystery force. He suggested that the protons and neutrons exchanged particles, creating the force to hold them together.

FIGURE 1 Timeline of the key moments in the understanding of strong nuclear force

CHECK YOUR LEARNING 4.4

Investigate, evaluate and communicate

1 **Investigate** the following question: Was the strong nuclear force 'invented' in the 1970s or was it 'discovered'? Did it exist before 1970? If so, where was it hiding; if not, what held nucleons together?

Your task is to investigate the strong nuclear force to make a claim (a 'thesis') about whether it was 'invented' or 'discovered'. To do this, complete the following:

a **Identify** the relevant scientific concepts.

b **Generate** and **interpret** evidence in support of the claim.

c **Evaluate** the quality of the evidence in a strongly worded conclusion.

d **Devise** a rebuttal of any evidence that opposes your claim.

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» **Increase your knowledge**
Valid and reliable research

» **Weblink**
The strong nuclear force

» **Weblink**
Rutherford

1938
Hans Bethe calculated in detail how nuclear fusion is able to power the Sun. The smashing together of nucleons brings them extra close, so the strong nuclear force gets even stronger and forms a combined nucleus.

1938
Otto Hahn and Lise Meitner bombarded uranium with neutrons to separate nucleons enough that the short-distance strong force acted little between them and they broke apart. This process is called nuclear fission.

1964
Murray Gell-Mann proposed the existence of quarks as the fundamental particles that make up protons and neutrons. The strong nuclear force holds most ordinary matter together because it confines quarks into particles such as the proton and neutron.

CHAPTER 4

Review

Summary

4.1

- The nuclear model of the atom is characterised by a small nucleus surrounded by electrons.
- Atoms are characterised by their number of protons (their atomic number).
- For a given element, different numbers of neutrons produce different isotopes and hence nuclides of different atomic mass.
- Atomic mass equals the sum of the numbers of protons and neutrons.
- The mass of a nucleus is always less than the combined individual masses of its component nucleons.

4.2

- The difference in mass is called the mass defect. This represents the binding energy, which is equivalent to the energy released during the formation of a nucleus, and is the energy that must be applied to the nucleus to break it apart. It can be calculated using Einstein's equation $E = mc^2$.
- Protons in the nucleus repel each other because they have the same charge.

4.3

- The force that binds the nucleons together is called the strong nuclear force.
- The strong nuclear force is one of the four fundamental forces. It acts over small distances in the nucleus to hold the nucleons together against the repulsive electrostatic forces exerted between the protons.
- The stability of a nuclide depends on its binding energy per nucleon – the greater this value, the more stable the nuclide.
- The stability of a nuclide is a result of the strong nuclear force over very short distances, electrostatic repulsion, and the relative number of protons and neutrons in the nucleus.
- The SI unit of atomic mass is the unified atomic mass unit (u).
- A mass of one unit (u) is equivalent to 931.5 MeV of energy or 1.66×10^{-27} kg.

Key terms

- atomic number
- atomic weight
- binding energy
- electrostatic repulsion
- electron volt (eV)
- elementary particles
- fundamental forces
- isotopes
- mass defect
- neutrons
- nuclear stability
- nucleons
- nucleus
- nuclides
- protons
- radioactive
- relative atomic mass
- stable
- strong nuclear force

Key formulas

Mass defect	$\Delta m = m_{cp} - m_{nuc}$
Theory of relativity	$\Delta E = \Delta mc^2$

Revision questions

The relative difficulty of these questions is indicated by the number of stars beside each question number: ★ = low; ★★ = medium; ★★★ = high.

Multiple choice

1 Which of the following options lists three types of forces in nature in order of decreasing strength?

A strong nuclear, electromagnetic, gravitational

B electromagnetic, strong nuclear, gravitational

C strong nuclear, gravitational, electromagnetic

D all are the same

2 Isotopes are nuclei with:

A same *A* and *Z*

B same *A*, different *Z*

C same *Z*, different *A*

D *Z* greater than *A*

3 The nuclide $^{56}_{26}Fe$ has a binding energy of 492 MeV. The binding energy per nucleon is:

A 6 MeV

B 8.8 MeV

C 16.4 MeV

D 18.9 MeV

4 Consider the nuclide $^{239}_{92}U$. If one extra nucleon could be added, what are the possible formulas for it?

A $^{240}_{92}U$ and $^{240}_{93}Np$

B $^{240}_{92}U$ and $^{240}_{93}U$

C $^{240}_{92}U$ and $^{239}_{93}Np$

D $^{239}_{93}Np$ and $^{240}_{93}Np$

5 A nucleus becomes increasingly unstable when there is a surplus of:

a protons over electrons

b electrons over protons

c protons over neutrons

d neutrons over protons

Short answer

Describe and explain

★ 6 **Define** nuclide, nucleon, neutron, nucleus, nuclei, nuclear.

★ 7 **Define** atomic number, binding energy, binding energy per nucleon, electron volt, elementary particle, fundamental forces, isotope, mass defect, mass number, material, matter, strong nuclear force, unified atomic mass unit.

★ 8 **Calculate** the number of protons and neutrons in each of these nuclides:

a $^{32}_{15}P$

b Zn-65

c Ba-136

★ 9 **Calculate** the number of protons and neutrons in each of the following:

a $^{207}_{82}Pb$

b $^{35}_{17}Cl$

c $^{15}_{7}N$

d At–215

e Bi–216

★ 10 **Identify** which of the following particles is acted on by both the strong nuclear force and the electromagnetic force and **explain**.

A proton

B neutron

C electron

D electron antineutrino

★ 11 **Identify** which one of the following lists three fundamental forces in increasing order of strength and **explain**.

A electromagnetic, weak nuclear, strong nuclear

B weak nuclear, gravity, strong nuclear

C gravity, weak nuclear, electromagnetic

D electromagnetic, strong nuclear, gravity

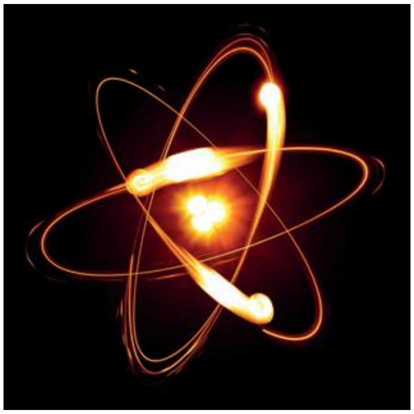

FIGURE 1 The fundamental forces hold an atom together.

★ **12** Complete Table 1 to **describe** the composition of the nuclide.

TABLE 1

Symbol	Symbol	Protons	Neutrons	Nucleons	*A*	*Z*
$^{64}_{28}Ni$	Ni-64					
	P-30					
		29	35			
			35			30
	Kr-?			83		
					136	56
$^{228}_{89}?$						

★★ **13** **Recall** why there are more neutrons than protons at high mass numbers.

★★ **14** **Calculate** the following for calcium isotopes with mass numbers of 40, 42, 43 and 45:

- **a** their symbols
- **b** the number of neutrons each has
- **c** the number of nucleons each has.

★★ **15** **Calculate**, for the following nuclides, the:

- **i** mass defect
- **ii** binding energy (MeV/nucleon).
  - **a** $^{35}_{15}S$
  - **b** $^{235}_{92}U$
  - **c** Cd–113
  - **d** Li–7

Apply, analyse and interpret

★ **16** A small piece of gold has a volume of 10 mm^3. It can be beaten out into a piece of gold leaf of area 100 cm × 50 cm.

- **a** **Calculate** the thickness of this leaf.
- **b** **Determine** how many atoms thick the foil is if the diameter of a gold atom is 2.7×10^{-12} m.

FIGURE 2 A small piece of gold

★ **17** **Determine** which element is represented by X in each of the following:

- **a** $^{233}_{92}X$
- **b** $^{2}_{1}X$
- **c** $^{226}_{88}X$
- **d** $^{32}_{15}X$

★★ **18** **Distinguish** between the nuclear strong force and the electrostatic (Coulomb) force.

★★ **19** **Interpret** the table of exact nuclide masses (Appendix 1) to calculate the binding energy of the following in:

- **i** J
- **ii** J/nucleon
- **iii** MeV
- **iv** MeV per nucleon
  - **a** sodium atom $^{23}_{11}Na$
  - **b** Be-7
  - **c** K-40

Investigate, evaluate and communicate

★★ **20** **Propose** whether, in your body, are there more protons or neutrons.

FIGURE 3 The human body

★★ **21** **Justify** why it matters whether the masses of the nuclides (Appendix 1) include the mass of the electrons as well.

★★ **22** **Decide** which of the following is the correct definition of the binding energy of a nucleus.

- **A** the product of the binding energy per nucleon and the nucleon number
- **B** the minimum work required to completely separate the nucleons from each other
- **C** the energy that keeps the nucleus together
- **D** the energy released during the emission of an alpha particle

★★★ **23** **Determine** the answers to the questions below relating to a physicist who discovers a particle with a mass of 2.02733 u. It is neutral, so she assumes it is two neutrons bound together.

- **a** **Calculate** the binding energy.
- **b** What is unreasonable about this result?
- **c** What assumptions are unreasonable or inconsistent?

★★★ **24** **Interpret** the data in Table 2 (which shows the variation in total binding energy (MeV) against the atomic and mass numbers of selected nuclides) to test the claim below.

TABLE 2

Z	A	MeV
30	66	578.136
30	67	585.189
31	69	601.996
32	72	628.686
33	75	652.564
34	76	662.073
34	77	669.492
36	80	695.434
38	86	748.928
40	90	783.893

Claim: 'The more nucleons present, the greater the forces holding the nucleus together and hence the greater the binding energy necessary to pull it apart.'

- **a** **Justify** whether the data in Table 2 supports this statement.
- **b** **Determine** the graphical shape of the relationship (linear, etc).
- **c** **Determine** the mathematical relationship.
- **b** **Predict** if the trend line is likely to go through (0, 0).

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CHAPTER 5

Radioactive decay and half-life

Radioactivity and nuclear energy have become some of the most important issues facing society. The benefits to society could be immense, but so too are the problems they bring.

OBJECTIVES

→ Explain natural radioactive decay in terms of stability.

→ Define alpha radiation, beta positive radiation, beta negative radiation and gamma radiation.

→ Describe alpha, beta positive, beta negative and gamma radiation, including the properties of penetrating ability, charge, mass and ionisation ability.

→ Explain how an excess of protons, neutrons or mass in a nucleus can result in alpha, beta positive and beta negative decay.

→ Solve problems involving balancing nuclear equations.

→ Represent spontaneous alpha, beta positive and beta negative decay using decay equations, e.g.

$$^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\text{He}^{2+} + \gamma$$

$$^{60}_{27}\text{Co} \rightarrow {}^{60}_{28}\text{Ni} + {}^{0}_{-1}e + \bar{\nu}_e + \gamma$$

$$^{102}_{50}\text{Sn} \rightarrow {}^{102}_{49}\text{In} + {}^{0}_{+1}e + \nu_e + \gamma$$

→ Explain how a radionuclide will, through a series of spontaneous decays, become a stable nuclide.

→ Define half-life.

→ Solve radioactive decay problems involving whole numbers of half-lives.

Source: *Physics 2019 v1.2 General Senior Syllabus Queensland Curriculum & Assessment Authority*

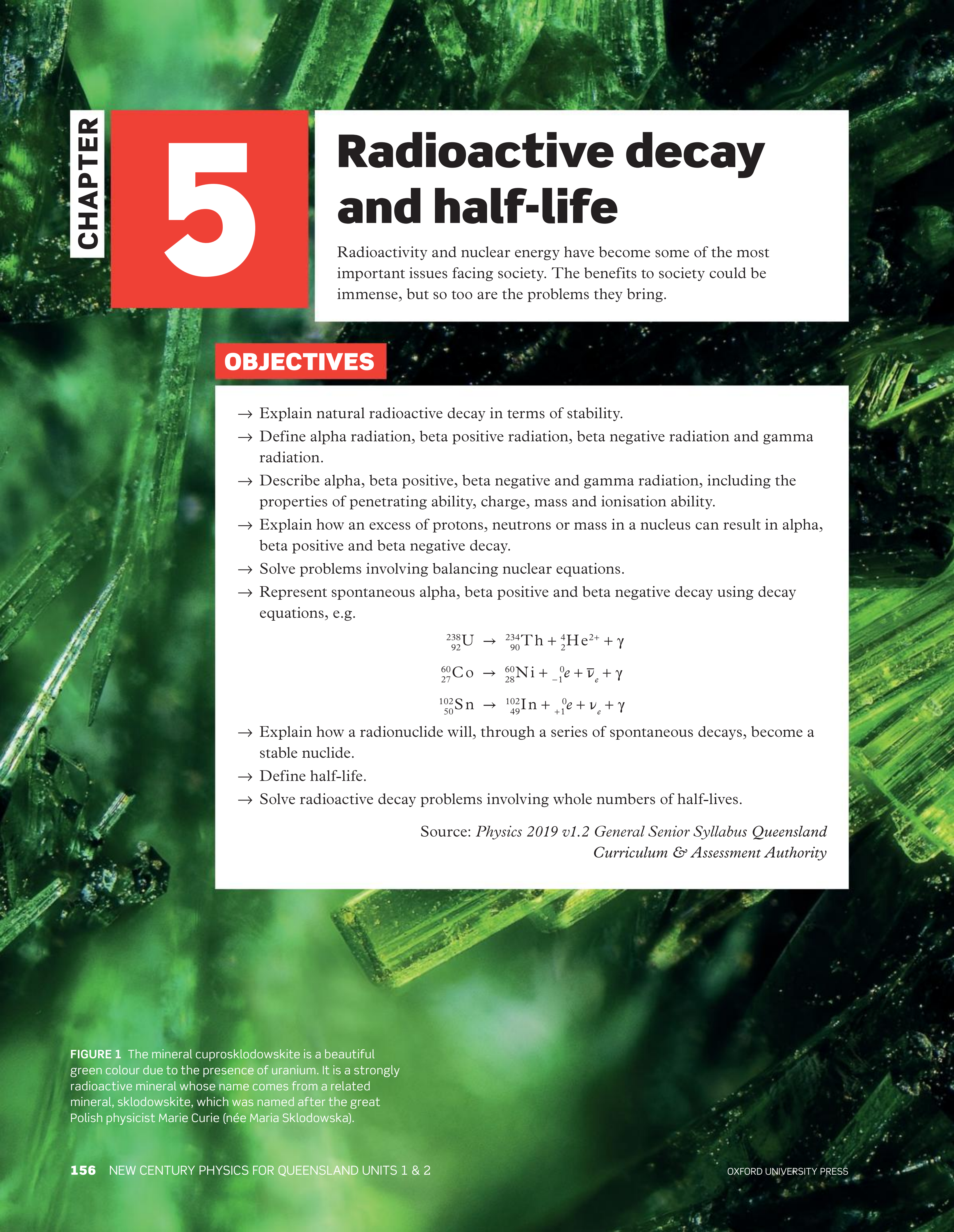


FIGURE 1 The mineral cuprosklodowskite is a beautiful green colour due to the presence of uranium. It is a strongly radioactive mineral whose name comes from a related mineral, sklodowskite, which was named after the great Polish physicist Marie Curie (née Maria Sklodowska).

MAKES YOU WONDER

In this chapter we will be examining some aspects of nuclear physics that will help to answer questions such as:

→ When you irradiate food with gamma rays, does the food become radioactive?

→ Can you accurately tell the age of bones that are millions of years old?

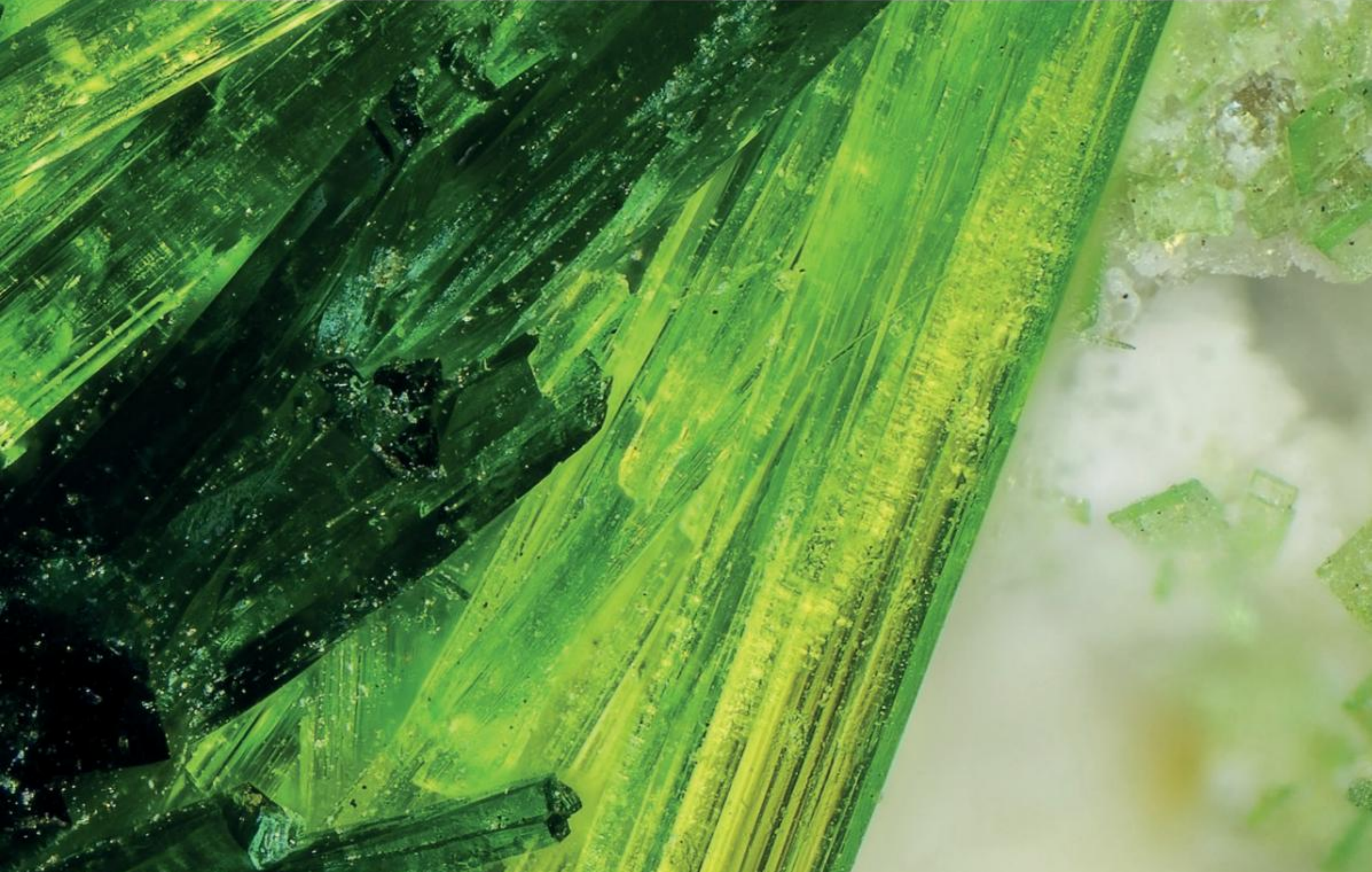
→ If gamma radiation can go straight through the body, how can it kill cancer tumours?

→ Why is an airline pilot exposed to more radiation than an air traveller?

→ Electrons are negatively charged, so how can you have a positive one?

PRACTICALS

SUGGESTED PRACTICAL	**5.1** Shielding effects from a radioactive source
SUGGESTED PRACTICAL	**5.2** Relationship between activity and distance from a radioactive source



5.1 The discovery of nuclear radioactivity

KEY IDEAS

In this section, you will learn about:

+ the discovery of nuclear radioactivity.

In 1896, French physicist Henri Becquerel (1852–1908) found (by accident) that a uranium-rich mineral called pitchblende emitted radiation that could pass through paper and blacken a photographic plate. He didn't follow up his discovery, but two years later a postgraduate student, Marie Curie, began her doctoral study of Becquerel's rays.

Marie Curie and her husband Pierre Curie, a well-known French physicist, soon discovered two new radioactive elements that she named polonium (after her native land Poland) and radium (because it radiates). Over the next four years they isolated a gram of radium salt from a tonne of pitchblende. Shortly after completing her PhD, Curie and Becquerel shared the 1903 Nobel Prize in Physics. Pierre Curie was killed in 1906, but Marie Curie continued her study of radioactivity for nearly 30 more years. She was awarded the Nobel Prize in Chemistry in 1911 for her discovery of two new elements. Marie Curie died of aplastic anaemia in 1934, most likely caused by exposure to radiation. Her books and papers are still radioactive, and you must put on gloves to handle them.

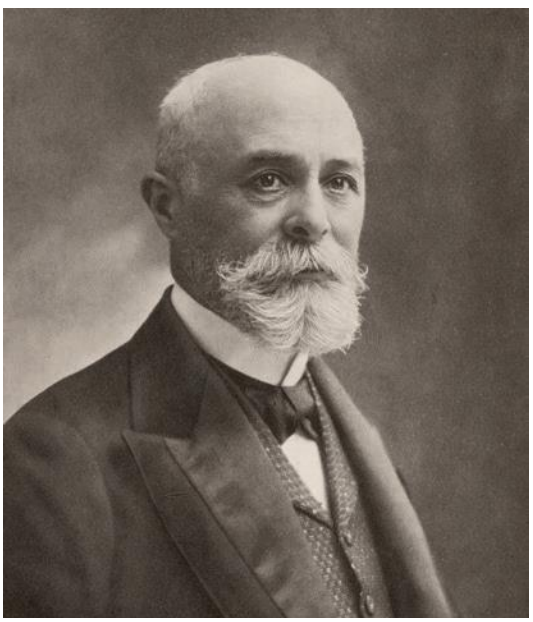


FIGURE 1 Physicist Henri Becquerel first discovered evidence of radioactivity in 1896.

FIGURE 2 Physicist Marie Curie co-discovered two radioactive elements: polonium and radium.

The particle 'zoo'

The 1930s saw a new burst of radioactivity research even greater than the two previous bursts in 1895 (Becquerel, Curie, Thomson) and 1912 (Rutherford, Bohr). In 1932, James Chadwick discovered the neutron and, very soon afterwards, American physicist Carl

SUGGESTED PRACTICAL

5.1 Shielding effects from a radioactive source
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Anderson discovered another fundamental particle – the 'positive electron' or **positron**. The existence of the positron had been predicted by Paul Dirac several years earlier. This was a major development in physics. Table 1 lists the important particles mentioned in this book so far. They are described fully in the next section.

positron
a particle of matter with the same mass as an electron but an opposite charge

TABLE 1 Symbols of nuclear particles/radiation

Particle	Symbol
Alpha particle (α)	${}^{4}_{2}He$
Proton	${}^{1}_{1}H$ or ${}^{1}_{1}p$
Neutron	${}^{1}_{0}n$
Electron (β^- particle)	${}^{0}_{-1}e$
Positron (β^+ particle)	${}^{0}_{+1}e$
Gamma ray	γ

FIGURE 3 Curie and Becquerel shared the 1903 Nobel Prize in Physics.

CHECK YOUR LEARNING 5.1

Describe and explain

1 **Recall** the name of the particle that before 1932 was thought to be the only particle in the nucleus.

2 **Recall** the name of the particle that Paul Dirac proposed before its existence was discovered years later. **Explain** what makes his discovery unusual.

3 **Construct** a table listing the six particles/radiation (alpha particle, proton, neutron, electron, positron and gamma ray) in the order they were discovered. For each, **identify** the date of discovery and who discovered it.

4 Use a periodic table to find out the symbols for the two elements isolated by Marie Curie. For each, **identify** how many protons it contains and how many electrons a neutral atom of the substance contains.

Investigate, evaluate and communicate

5 **Propose** why you need to wear gloves when handling Marie Curie's laboratory notebooks. **Assess** whether it is to stop the books getting dirty.

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» Suggested practical
5.1 Shielding effects from a radioactive source

» Weblink
Henri Becquerel

» Weblink
Marie Curie

5.2 Properties of nuclear radiation

KEY IDEAS

In this section, you will learn about:

- the properties of nuclear radiation
- alpha, beta positive, beta negative and gamma radiation
- how radiation can be detected.

Any radiation that can remove an electron from an atom and create a heavy positive ion and free electron is termed **ionising radiation**. Visible light won't do this as it lacks the energy – it simply gets absorbed and increases the object's thermal energy. The energy of **alpha radiation**, **beta positive radiation**, **beta negative radiation** and **gamma radiation** is about a million times greater than that of visible light, and it can ionise matter and break molecular bonds.

Ionising radiations include electromagnetic radiation (gamma rays, X-rays, and ultraviolet radiation) as well as energetic particles such as alpha and beta particles. Gamma rays are said to be **nuclear radiation** because they are created within the nucleus. X-rays are not nuclear radiation as they come from the electron cloud around the nucleus.

By the early 1900s, the properties of alpha, beta and gamma radiation had been measured, allowing physicists to better understand the process of radioactivity.

ionising radiation
radiation that can remove an electron from an atom and create a heavy positive ion and free electron

alpha radiation
stream of particles each consisting of two protons and two neutrons emitted from the nucleus of some radionuclides (symbol: α or ${}^{4}_{2}He$)

beta positive radiation
stream of energetic positrons (and associated neutrinos) emitted from an atomic nucleus during beta positive decay

beta negative radiation
stream of particles emitted from the nucleus that are identical to an electron (symbol: β^-)

gamma radiation
extremely high-frequency electromagnetic radiation emitted from the nucleus of some radionuclides (symbol: γ)

nuclear radiation
radiation in the form of elementary particles emitted by an atomic nucleus, as alpha, beta or gamma rays

Absorption and penetrating power

All three types of nuclear radiation produce ionisation in materials – they turn the atoms into ions by knocking electrons in or out. However, they penetrate different distances in materials – that is, they have different ranges (see Figure 1).

The range of radiation is the distance it can travel through a material. Range is related to several factors:

- Energy of the radiation – As radiation penetrates a material, it loses energy as it causes ionisation. Thus, more energy means it goes further before being stopped (just like a bullet in a target). Higher kinetic energy particle → higher range
- Type of radiation – Higher charge → lower range; higher speed → higher range
- Density of material encountered also determines the range – Higher density → lower range (Figure 2).

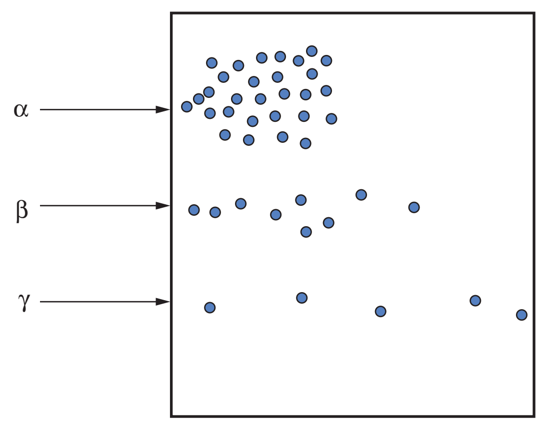

FIGURE 1 Penetrating power of the different forms of radiation. Not all alpha particles are the same. They can have different speeds and, as a result, different kinetic energies, and can penetrate to slightly different depths. The same is true of beta particles and gamma rays. The blue dots show the material being ionized by the raditation.

Alpha particles

An alpha particle (α) is just a helium nucleus, ${}^{4}_{2}He$ – it is made up of 2 protons and 2 neutrons strongly bound together. Having 2 protons means alpha particles have a +2 charge. As they collide with matter, alpha

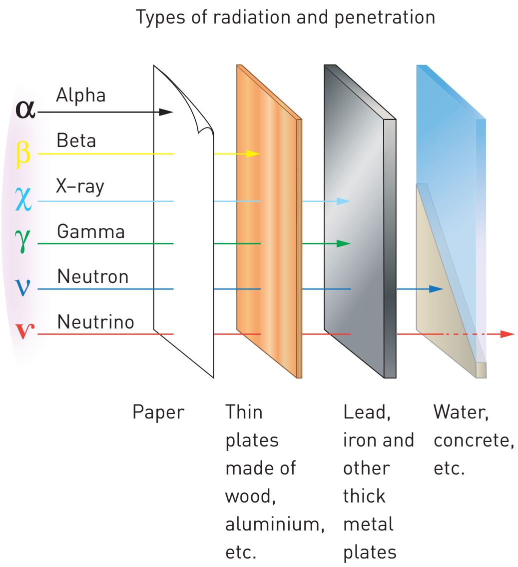

FIGURE 2 The relative penetrating power of the three types of nuclear radiation (alpha, beta, gamma) plus X-rays, neutrons and neutrinos for comparison, in substances of different thickness and density.

particles slow down, transferring their kinetic energy to the other molecules, shaking many of them apart, and leaving a trail of positive and negative ions in their wake.

Alpha particles have a relatively large mass, which makes them relatively easy to stop outside the body, but the electrical charge and energy of an alpha particle can cause damage to tissues over a short distance. Alpha particles are unable to penetrate the outer layer of dead skin cells, but if they are eaten in food or breathed in, they can cause serious cell damage.

Alexander Litvinenko is a famous example of someone whose death was caused by alpha particles. Litvinenko was a Russian secret service agent who claimed his superiors were corrupt. He fled to Britain, but a few years later was poisoned by polonium-210, an alpha emitter, in his tea.

Study tip

Information about deflection in a magnetic field can be found on your obook assess.

Beta negative particles

Beta negative particles (β^-) are electrons, ${}_{-1}^{0}e$, which move at high speed ranging from 0.3 to 0.99 times the speed of light (3×10^8 m s^{-1}), and thus have high kinetic energy. Due to their smaller mass, they can travel further in air than alpha particles, up to a few metres, and can be stopped by a thick piece of plastic or a stack of paper. Beta negative particles can penetrate skin a few centimetres, posing something of an external health risk. However, the main threat to human health is still primarily from internal emission from ingested material.

Beta positive particles

Beta positive particles (β^+) are high-energy, high-speed positrons (positive electrons, ${}_{+1}^{0}e$). They have the same penetrating properties as beta negative particles but are deflected in the opposite direction in a magnetic field.

Gamma radiation

Gamma radiation differs from alpha and beta radiation in that it is not made up of charged particles and is not deflected in electric or magnetic fields. Instead, gamma rays (γ) are electromagnetic radiation of extremely short wavelength (about 10^{-13} m), and thus a very high frequency (about 10^{21} Hz).

Since they have no charge, gamma rays have tremendous penetrating power because they interact with the absorbing material via a direct head-on collision with an electron or nucleus. Materials such as lead are good absorbers of gamma radiation, mainly because of their high electron density. Gamma rays can be stopped by a thick or dense enough layer of material. High atomic number materials, such as lead or depleted (non-radioactive) uranium, are the most effective form of shielding.

Of the three forms of radioactive decay, gamma rays are the most penetrating. However, under most circumstances, they cause the least amount of tissue damage over comparable distances.

Neutrinos and the neutrino problem

Neutrinos (ν) are tiny, uncharged, almost massless particles produced during radioactive decay. They were first proposed in theory in 1930 to solve the problem of the missing energy in the beta decay reaction see p. 167, but were not detected until 1956. *Neutrino* is Italian for 'little neutral one'.

The majority of the neutrinos in the universe were born around 15 billion years ago, soon after the birth of the universe in the Big Bang. Since this time, the universe has continuously expanded and cooled, and neutrinos have just kept on going. They are striking you right now. About 10^{13} neutrinos are passing through your head every second, but they do no damage as they hardly interact with matter because of their tiny size and lack of charge. Other neutrinos are constantly being produced from nuclear power stations, particle accelerators, nuclear bombs and during the birth, collisions and death of stars (particularly supernovae).

The current model for subatomic particles proposes six types of neutrinos: the electron neutrino (ν_e), the muon neutrino (ν_μ), the tau neutrino (ν_τ), and their antiparticles – the electron antineutrino ($\bar{\nu}_e$), the muon antineutrino ($\bar{\nu}_\mu$) and the tau antineutrino ($\bar{\nu}_\tau$). We will meet two of them again when we consider beta decay. Neutrinos have the Greek symbol ν, pronounced 'nu' (see pp. 167–168).

Detecting radiation

Ionising radiation is invisible – the only way you know it is present (other than by the damage it may be causing) is by use of a radiation detector. As mentioned earlier, Henri Becquerel used photographic paper to detect radiation in 1896. A more recent development was the radiation detector called the Geiger counter.

Geiger counters are commonly used to detect radiation and make a clicking and buzzing sound (you often see them in movies). The Geiger–Müller tube is the sensing component of a Geiger counter. The tube is connected to a counter that gives a visual and audible display of the 'count' as the particles ionise the gas inside the tube (see Figure 3).

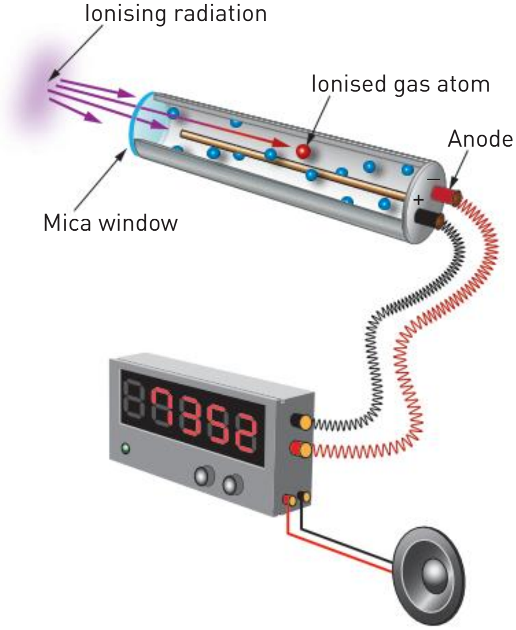

FIGURE 3 The Geiger–Müller tube is the sensing component of a Geiger counter. Note that the rod is along the centre of the tube and there is a thin mica window at the end. Mica is fairly low density, so it doesn't absorb much radiation.

A Geiger–Müller tube consists of a metal cylinder with a wire along its axis, and it is filled with an insulating gas such as argon or neon. A high voltage is applied across the wire and cylinder, but no current flows until ionising radiation passes into the tube. When it does, the radiation ionises the gas and produces free ion pairs that constitute a current, which is detected as a count. Geiger counters don't identify the energy, charge or type of radiation.

SUGGESTED PRACTICAL

5.2 Relationship between activity and distance from a radioactive source
Go to your obook assess »

FIGURE 4 If alpha particles are eaten or breathed in, they can cause serious cell damage; hence the use of protective gear in radioactive areas.

CHECK YOUR LEARNING 5.2

Describe and explain

1 **Explain** why alpha particles are easy to stop.

2 **Explain** why alpha particles are not all the same and have different penetrating abilities even though they are all made of 2 protons and 2 neutrons.

3 **Explain** why β^+ and β^- particles move differently in a magnetic field.

Apply, analyse and interpret

4 **Determine** why an alpha particle is considered dangerous even though it can't penetrate human skin.

5 **Determine** how many minutes it will take a neutrino to travel from the Sun to Earth, a distance of 150 million km, at the speed of light (3×10^8 m s^{-1}).

Evaluate, investigate and communicate

6 **Propose** a reason why a gamma ray and a neutron have the same deflection in a magnetic field.

7 **Propose** a reasoned estimate of how many neutrinos must pass through the floor of your lab per second given that 10^{13} neutrinos pass through the top of your head in the same time.

Check your obook assess for these additional resources and more:

» Student book questions
Check your learning 5.2

» Suggested practical
5.2 Relationship between activity and distance from a radioactive sources

» Video
Geiger counter

» Increase your knowledge
Deflection in a magnetic field

OI GI

5.3 Radioactive decay and balancing equations

KEY IDEAS

In this section, you will learn about:

+ the process of radioactive decay
+ how to balance equations showing radioactive decay.

Study tip

In the products of a reaction, the particle can be written before or after the daughter nucleus. There is no preference.

Study tip

1. **The number of protons (atomic number) determines the name and symbol of the element.** When trying to work out the symbol for the daughter nucleus, students often make the mistake of using the mass number (*A*) and not the atomic number (*Z*).
2. **If you had two alpha particles given off in a reaction, they would be written as** $2\,^{4}_{2}\mathrm{He}$. You would think of the two alpha particles as $^{4}_{2}\mathrm{He} + ^{4}_{2}\mathrm{He}$, even though it would be written as $2\,^{4}_{2}\mathrm{He}$. This is very important in the next chapter.

The world is made up of stable nuclei – atoms don't all just disintegrate in front of us! But there are some atoms that are radioactive and decay or disintegrate into other types of atoms. Some nuclei, such as palladium-221, may only last for 6 microseconds, whereas lead-206 will last for billions of years and is said to be infinitely stable. Between these two extremes are nuclei that may exist for seconds, hours, days or years before decaying. Another isotope of lead, lead-214, will last for 27 minutes (on average) before decaying.

When the original unstable 'parent' nucleus decays, it produces a 'daughter' nucleus and at least one other particle. The reaction can be written like the normal chemical equation:

Parent nucleus → daughter nucleus + particle(s)

For example:

$$\text{uranium-238} \rightarrow \text{thorium-234} + \text{alpha particle}$$
$$^{238}_{92}\mathrm{U} \rightarrow ^{234}_{90}\mathrm{Th} + ^{4}_{2}\mathrm{He}$$

We must check if the equation is 'balanced', as we do with chemical reactions. When an equation is balanced, it means the mass numbers and charge are equal on both sides. To balance a decay reaction:

- **The sum of the mass numbers on the left of the equation must be the same as the sum of the mass numbers on the right side.** In the example above, 234 + 4 = 238, so this rule is obeyed.
- **The total charge on the left side of the equation must equal the total charge on the right side.** 'Charge' refers to the nuclear charge and that of its emitted particles. A proton has a charge of +1, and so does a beta positive particle (a positron, β^+). An electron (β^- particle) has a charge of –1. In the example above, the left side shows 92 protons so the charge is +92 or simply 92. The sum of the nuclear charges on the right is 90 + 2 = 92, so the rule is obeyed.

WORKED EXAMPLE 5.3

Balance the following radioactive decay: $^{226}_{88}\mathrm{Ra} \rightarrow ^{4}_{2}\mathrm{He} + ?$

SOLUTION

Step 1: The mass numbers (top numbers) must be equal to 226 on both sides, so the daughter nucleus must have a mass number of 226 – 4 = 222.

Step 2: The nuclear charges (bottom numbers) must be equal to 88, so the daughter nucleus must have a charge of 88 – 2 = 86.

Step 3: The nuclear charge (atomic number) determines the name of the element. *Z* = 86 refers to radon. Note: the top number (222) is **not** used to find the name of the atom.

Step 4: Write the balanced equation: $^{226}_{88}\mathrm{Ra} \rightarrow ^{4}_{2}\mathrm{He} + ^{222}_{86}\mathrm{Rn}$

FIGURE 1 Some atoms are radioactive and decay or disintegrate into other types of atoms.

CHECK YOUR LEARNING 5.3

Describe and explain

1 **Recall** the two rules for balancing an equation.

2 **Identify** the nuclear charge on ${}^{14}_{6}C$.

3 **Explain** what the symbol $3\,{}^{0}_{+1}e$ represents.

Apply, analyse and interpret

4 **Clarify** how you determine the number of neutrons in $2\,{}^{4}_{2}He$.

5 **Analyse** the following symbols to determine the number of protons and neutrons that are present:

a ${}^{234}_{92}U$

b Th-230

6 **Derive** the symbol (in ${}^{A}_{Z}X$ format) of an atom with 24 protons and 30 neutrons.

7 **Determine** the products of the following part-equations:

a ${}^{214}_{83}Bi \rightarrow {}^{0}_{-1}e + ?$

b ${}^{239}_{93}Np \rightarrow {}^{0}_{+1}e + ?$

c ${}^{226}_{88}Ra \rightarrow {}^{222}_{86}Rn + ?$

d ${}^{45}_{20}Ca \rightarrow {}^{0}_{-1}e + ?$

e ${}^{58}_{29}Cu \rightarrow {}^{0}_{+1}e + ?$

f ${}^{234}_{94}Pu \rightarrow {}^{4}_{2}He + ?$

Evaluate, investigate and communicate

8 **Assess** why this equation appears balanced but contains errors: ${}^{5}_{7}N \rightarrow {}^{5}_{6}C + {}^{0}_{+1}e$.

Check your obook assess for these additional resources and more:

» Student book questions
Check your learning 5.3

» Increase your knowledge
Balancing equations

» Weblink
Atoms and radioactivity

» Weblink
Radioactive decay

5.4 Types of decay

KEY IDEAS

In this section, you will learn about:

+ alpha, beta positive, beta negative and gamma decay
+ how to predict the type of decay.

There are three main ways that nuclei decay naturally: alpha decay, beta negative (electron) decay and beta positive (positron) decay. The name of each indicates what sort of particle is produced.

These types of decay are associated with three unstable states of a nuclide:

- too many protons and neutrons – too much mass (alpha decay)
- too many neutrons (beta negative decay)
- too many protons (beta positive decay).

Alpha decay – the helium nucleus

alpha decay
the emission of a $^{4}_{2}\mathrm{He}$ nucleus (2 protons, 2 neutrons) from the parent nucleus

Alpha decay (α) is the emission of a $^{4}_{2}\mathrm{He}$ nucleus (2 protons, 2 neutrons) from the parent. The daughter nucleus has two fewer protons and two fewer neutrons than the parent.

Alpha decay occurs when there is too much mass.

For example, atoms heavier than uranium-238 do not occur naturally. We can produce them artificially, but they have too many neutrons and protons to be stable. In other words, they have too much mass for the nuclear 'glue' to work. Such atoms decay by alpha emission, and the parent nucleus loses 2 protons and 2 neutrons as a fast-moving, energetic alpha particle (Figure 1).

$$\text{Alpha decay: } ^{A}_{Z}\mathrm{X} \rightarrow \, ^{A-4}_{Z-2}\mathrm{Y} + \, ^{4}_{2}\mathrm{He} + \text{energy } (\gamma)$$

$$\text{For example: } ^{236}_{91}\mathrm{Pa} \rightarrow \, ^{232}_{89}\mathrm{Ac} + \, ^{4}_{2}\mathrm{He} + \gamma$$

Note that the mass number of the atom is less in the product (232) than in the reactant (236). It has shed some mass.

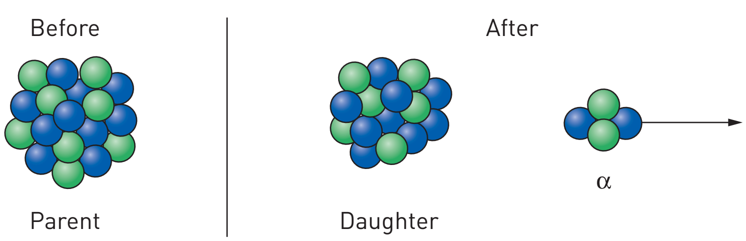

FIGURE 1 In alpha decay, mass is shed in the form of alpha particles.

Alpha decay occurs because the strong nuclear force is unable to hold large nuclei together. Because the strong nuclear force is a short-range force, it acts only between neighbouring nucleons. However, the repulsive electrostatic force can act across the whole nucleus. For very large nuclei, the large number of protons means the total repulsive force is great compared with the attractive strong nuclear force, which cannot hold the nucleus together. The only way to achieve stability is to shed some protons and neutrons. This occurs in packets of 2p and 2n – that is, the helium nucleus $^{4}_{2}\mathrm{He}$, known as an alpha (α) particle.

The daughter nuclides produced by alpha decay often have their neutrons and protons in an 'excited' (high energy) state. The excess energy associated with this excited state is released when the nucleus emits a photon in the gamma ray (γ) portion of the electromagnetic spectrum. Most of the time, the gamma ray is emitted within 10^{-12} seconds after the alpha particle. In some cases, gamma decay is delayed, and a 'metastable' or short-lived nuclide is formed. This is identified by a small letter *m* written after the mass number. For example, ${}^{60m}_{27}\mathrm{Co}$ is produced by the beta negative decay of ${}^{60}\mathrm{Fe}$.

Study tip

In some books, beta negative and beta positive particles are called 'beta minus' and 'beta plus' particles.

Beta negative decay – the electron

There are two types of beta particles: beta negative (the electron) and beta positive (the positron). Each type is associated with a different type of instability in a nuclide. **Beta negative decay** (β^-) occurs when there are too many neutrons in the nucleus for the number of protons.

beta negative decay
emission of beta negative particles (electrons) from the parent nucleus

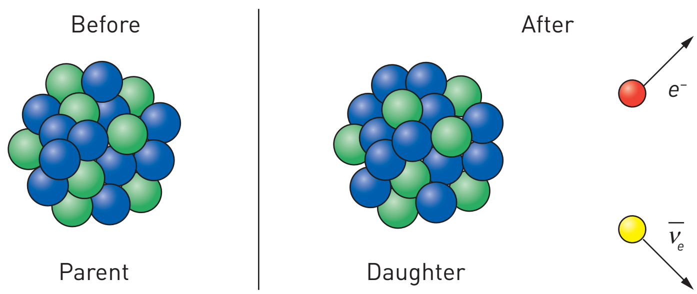

FIGURE 2 Example of β^- decay in which the parent nucleus emits an electron and an electron antineutrino. The daughter nucleus has one more proton and one fewer neutrons than its parent. Neutrinos interact so weakly that they are almost never directly observed, but they play a fundamental role in particle physics and should be included in your equations.

A beta negative particle is an electron that has come from the nucleus. The symbol ${}^{0}_{-1}\mathrm{e}$ stands for an electron whose charge is –1 (i.e. $Z = -1$) and negligible mass (the mass number $A = 0$). It can also be written as β^-. When a parent nucleus emits a beta particle, the daughter nuclide produced has the same mass number as the parent:

$$\text{Beta negative decay: } {}^{A}_{Z}\mathrm{X} \rightarrow {}_{Z+1}^{\;\;A}\mathrm{Y} + {}^{0}_{-1}\mathrm{e} + \bar{\nu}_e + \gamma \text{ (energy)}$$

Two examples of beta negative decay:

$${}^{239}_{92}\mathrm{U} \rightarrow {}^{239}_{93}\mathrm{Np} + {}^{0}_{-1}\mathrm{e} + \bar{\nu}_e + \gamma \text{ (energy)}$$

$${}^{234}_{91}\mathrm{Pa} \rightarrow {}^{234}_{92}\mathrm{U} + {}^{0}_{-1}\mathrm{e} + \bar{\nu}_e + \gamma \text{ (energy)}$$

It can be seen in these examples that the number of nucleons has not changed, but the daughter has one more proton than the parent. It is as if one of the neutrons has changed into a proton and, in the process (to conserve charge), has given off an electron. In fact, neutrons decay in this manner. Outside the nucleus, neutrons only last for about 10.2 minutes before the reaction occurs where the neutron decays into a proton, an electron and an electron antineutrino:

$${}^{1}_{0}\mathrm{n} \rightarrow {}^{1}_{1}\mathrm{p} + {}^{0}_{-1}\mathrm{e} + \bar{\nu}_e$$

In the 1920s, accurate measurements of the masses of reactants and products in beta decay showed that the masses were not equal. Some mass appeared to be lost. Physicists were troubled at the prospect of the law of conservation of mass being violated. In 1930, Wolfgang Pauli proposed an alternative solution: the missing mass was being carried off by a particle of zero charge and negligible mass that made it difficult to detect. The Italian physicist Enrico Fermi (1901–1954) suggested the name **neutrino**, meaning 'little neutral one'.

neutrino
an elementary subatomic particle very similar to an electron, but without electrical charge and with a very small mass

antineutrino an elementary subatomic particle without electrical charge and with a very small mass

antiparticle a particle with the same mass and opposite charge to a corresponding particle, for example positron and electron

beta positive decay emission of beta positive particles (positrons) from the parent nucleus

Study tip

If you are finding it hard to remember which type of nuclide instability is associated with which particle, try remembering the following:

'Too many **N**eutrons give beta **N**egative'

'Too many **P**rotons give beta **P**ositive'.

The symbol for the neutrino is the Greek letter nu (ν). A bar is placed over the symbol ($\overline{\nu}$) to indicate that, in beta negative decay, an antineutrino is formed. The bar means 'anti'. An **antineutrino** is an **antiparticle** to the normal neutrino (this will be covered further in Unit 4). Neutrinos are flooding through everything right now, because nothing much stops them. It has been estimated you would need a lead block 90 light years thick to stop about 50% of them.

Beta positive decay – the positron

A positron is a positive electron, represented as ${}^{0}_{+1}e$, β^+ or e^+. It has the same mass as an electron ($A = 0$), but it has the opposite charge. Therefore, its atomic number is said to be $Z = +1$, the same as its charge.

Beta positive decay (β^+) is also known as positron decay.

Beta positive decay occurs when there are too many protons in the nucleus for the number of neutrons.

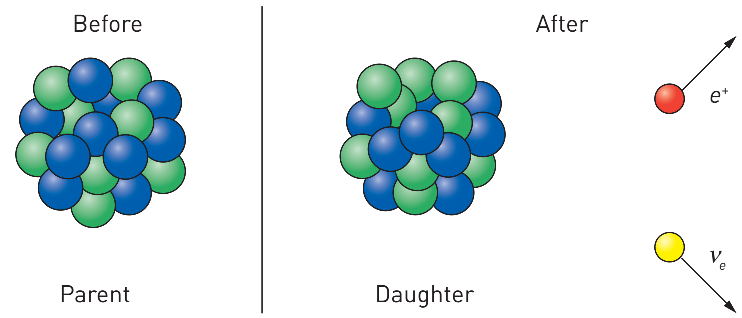

FIGURE 3 β^+ decay is the emission of a beta positive particle (positron) that eventually combines with an electron to annihilate each other (resulting in the emission of a gamma ray).

In beta positive decay, the number of nucleons (the top number) does not change. But, as the number of protons decreases, it appears that a proton has been changed into a neutron and a positron ejected along with an electron neutrino:

$${}^{1}_{1}p \rightarrow {}^{1}_{0}n + {}^{0}_{+1}e + \nu_e$$

However, an isolated proton **does not** turn into a neutron and a positron. This would seem impossible as the mass of a neutron is heavier than that of a proton. Positron emission occurs when the nucleus of an atom rearranges. The binding energy of the parent nuclide will be heavier than that of the daughter and positron, so it all makes sense. Just remember: protons do **not** decay in isolation (they have a half-life of 10^{31} years or more). What a proton decays into is anyone's guess – it could form particles such as a positron, or something more exotic like the subatomic particle called a neutral pion (to be dealt with in Unit 4).

The positron produced by beta positive decay soon collides with an electron and they annihilate each other, giving out a burst of gamma rays. The gamma rays travel in opposite directions – a process made use of in positron emission tomography (PET):

$${}^{0}_{+1}e + {}^{0}_{-1}e \rightarrow 2\gamma$$

Two examples of beta plus emission (along with an ejected electron neutrino ν_e):

$${}^{23}_{12}Mg \rightarrow {}^{23}_{11}Na + {}^{0}_{+1}e + \nu_e$$

$${}^{40}_{19}K \rightarrow {}^{40}_{18}Ar + {}^{0}_{+1}e + \nu_e$$

English physicist Paul Dirac predicted the existence of the positron in the late 1920s. American physicist Carl Anderson was awarded the Nobel Prize in 1936 for his discovery of the positron in a cosmic ray shower. It is now believed that all particles have antiparticles: protons and their antiprotons for example. There may be a region of the universe where everything is made up of antiparticles. Imagine shaking hands with someone from there – you would both disappear in an instant.

CHALLENGE 5.4A

Electron capture

Electron capture is another process often placed under the heading of beta decay. During electron capture, an electron in an atom's inner shell is drawn into the nucleus where it combines with a proton, forming a neutron and a neutrino. The neutrino is then ejected from the atom's nucleus. The capture of an electron has the same effect on a nucleus as the emission of a positron, so it is like beta positive decay – one of the constituent protons transforms into a neutron, and the total electric charge diminishes by 1. Electron capture, along with beta positive decay, is a way to fix a nucleus that is too proton-rich.

For example:

$$^{239}_{96}\text{Cm} + {}^{0}_{-1}e \rightarrow {}^{239}_{95}\text{Am} + {}^{0}_{0}\nu$$

Write full equations for the electron capture of Ar-38 and for K-40.

Gamma decay

Gamma radiation is released during the **gamma decay** of an atomic nucleus from a high-energy 'excited' state to a lower energy state. It is similar to what you learnt in previous years about the transitions of electrons from one 'excited' energy level (shell) to a lower level, in which electromagnetic radiation was emitted. You may have carried out the 'flame colour' experiment, where you placed different solutions of metal nitrates in a Bunsen flame and saw beautiful colours burn (copper → green, calcium → red). Similarly, when protons or neutrons in the nucleus drop from an excited level to a lower one, energy in the form of gamma radiation is emitted. Gamma photons (particles of radiation) have a million times more energy (typically 1 MeV) than photons of visible light (typically 1 eV).

gamma decay
a form of radioactivity in which an unstable atomic nucleus dissipates energy by emitting gamma radiation

Study tip

Information about predicting the type of decay can be found on your obook assess.

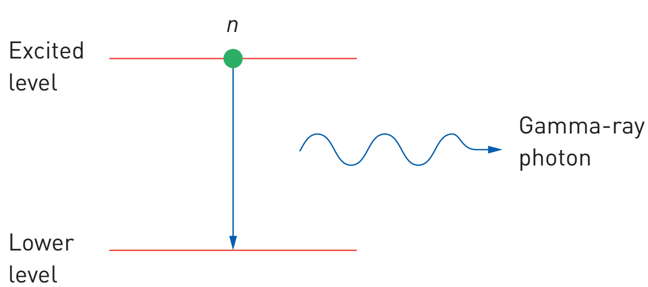

FIGURE 4 Gamma decay of an atomic nucleus

transmutation
the change of one chemical element into another by a nuclear reaction

In pure gamma decay there is no change to the numbers of protons or neutrons, and therefore no **transmutation**. It is a release of energy in the form of electromagnetic radiation of a particular wavelength and frequency that originates from within the nucleus. On the other hand, an X-ray is an electromagnetic radiation originating from the electron cloud surrounding the nucleus.

The following equation shows Co-60 undergoing beta decay to form an 'excited' Ni-60 nucleus (as indicated by the asterisk), which then decays to the ground state by two successive gamma ray emissions:

$$^{60}_{27}\text{Co} \rightarrow {}^{60}_{28}\text{Ni}^{\star} + {}^{\ 0}_{-1}\text{e} + \gamma \ (1.17 \text{ MeV})$$
$$^{60}_{28}\text{Ni}^{\star} \rightarrow {}^{60}_{28}\text{Ni} + \gamma \ (1.33 \text{ MeV})$$

Decay series

decay series
a sequence of nuclides formed by successive radioactive decays until a stable decay product, the end product, is formed

Sometimes a radioactive isotope decays into another daughter isotope that is also radioactive. This daughter isotope decays into another isotope, which decays further and so on. This successive chain of decays is called a **decay series**.

Figure 5 shows the uranium–lead decay series. U-238 decays by alpha emission to Th-234, which in turn decays by beta emission, and so on until the stable isotope Pb-206 is reached. In an alpha decay, $^{4}_{2}\text{He}$ is lost so the atomic mass decreases by 4 and the atomic number decreases by 2. This appears as a diagonal arrow in the decay series. Beta negative emission (in which n → p) has no effect on atomic mass, so it appears as an arrow pointing to the right. Beta positive emission appears as an arrow pointing to the left.

In the uranium–lead decay series (Figure 5), note that there are several paths the sequence can take. For example, Po-218 can decay by alpha emission to Pb-214 or by beta negative emission to At-218, and so on. The series ends at the stable lead isotope Pb-206. Other radioactive series also exist.

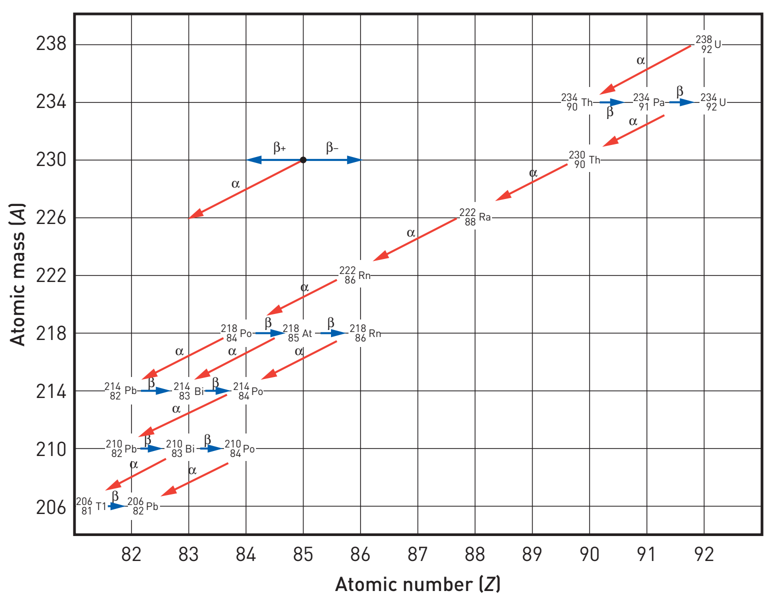

FIGURE 5 The uranium-lead decay series: nuclide decay to Pb-206 via a number of different routes

FIGURE 6 Surfers Paradise, Gold Coast

CHALLENGE 5.4B

ANSTO

Scientists from the Australian Nuclear Science and Technology Organisation (ANSTO) measured the U/Pb ratio in Gold Coast beach sand. They found it was Precambrian sand from the Antarctic that was 600 million years old. Using the decay series graph, state the relationship between U and Pb and explain how the ratio can indicate the age of a rock.

CHECK YOUR LEARNING 5.4

Describe and explain

1 **Explain** the differences between alpha, beta positive, beta negative and gamma decay.

2 **Describe** what is meant by a decay series.

3 **Describe** the type of decay that occurs when there is a surplus of protons.

Apply, analyse and interpret

4 **Determine** equations for the beta negative decay of:

a C-14

b Na-24

c P-32

5 **Determine** equations for the beta positive decay of:

a ^{22}Na

b ^{18}F

6 **Deduce** and **explain** the meaning of the following equations, which represent a two-stage decay of the nuclide $^{241}_{95}$Am to an excited $^{237}_{93}$Np nucleus (indicated with asterisk) that decays with the emission of a gamma ray.

a $^{241}_{95}\text{Am} \rightarrow {}^{237}_{93}\text{Np}^* + {}^{4}_{2}\text{He}$

b $^{237}_{93}\text{Np}^* \rightarrow {}^{237}_{93}\text{Np} + \gamma$

7 **Determine** the composition of two new heavy nuclides that have been prepared recently, given these incomplete equations:

$^{249}_{98}\text{Cf} + {}^{12}_{6}\text{C} \rightarrow 4{}^{1}_{0}\text{n} + ?$

$^{242}_{94}\text{Pu} + {}^{22}_{10}\text{Ne} \rightarrow 4{}^{1}_{0}\text{n} + ?$

Investigate, evaluate and communicate

8 **Construct** an equation showing the two steps in the beta negative decay of Ir-192, which produces an intermediate excited nuclide that further decays by gamma emission. Hint: remember what accompanies β^- decay.

9 **Evaluate** this statement: ‘Beta positive decay and electron capture are the same thing’.

Check your obook assess for these additional resources and more:

» Student book questions
Check your learning 5.4

» Challenge
5.4A Electron capture

» Challenge
5.4B ANSTO

» Video
Activity vs Distance

OI

5.5 Half-life

KEY IDEAS

In this section, you will learn about:

+ how to define and calculate half-life.

Radioactive decay is a random event, just as a car accident is a statistically random event. There is no means of predicting whether a particular driver will be involved in a crash. However, it is possible to say, statistically, how many crashes will happen in Australia each year. The more cars, the more accidents. Likewise, if you throw 100 coins into the air, you can reliably predict that about 50 will come down heads and 50 tails, but you can't say what a particular coin will do.

In a similar way, it is quite impossible to predict when a particular nucleus will decay, but it is possible to predict the number of nuclei that will decay in a given time from a particular source. For example, N-13 decays to C-12 by beta positive emission:

$$^{13}_{7}\mathrm{N} \rightarrow {}^{12}_{6}\mathrm{C} + {}^{0}_{+1}\mathrm{e} + \nu_e$$

If we started with a sample containing 10 000 N-13 atoms, after 10 minutes there would be about 5000 N-13 atoms left (half the starting number) and the rest would have decayed into C-12. When another 10 minutes has elapsed, there would be about 2500 atoms of N-13 left, and a further 10 minutes would take us down to 1250 atoms of N-13. The period of 10 minutes in which half the N-13 atoms decay is called the **half-life** ($t_{\frac{1}{2}}$).

half-life
the time taken for half the radioactive atoms in a sample to decay

TABLE 1 Decay of a sample of N-13

Time elapsed, *t* (minutes)	Number of N-13 atoms remaining, *N*
0	10 000 (= N_o)
10	5000
20	2500
30	1250
40	625

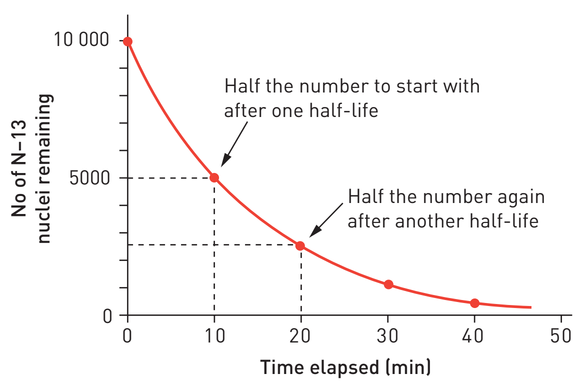

FIGURE 1 Plot of decay data from Table 1. Note that $t_{\frac{1}{2}}$ = 10 minutes.

We can develop a formula that relates the number of radioactive nuclei remaining with the number at the start and the time elapsed (Table 2).

TABLE 2 Determining the number of radioactive nuclei remaining

n = number of half-lives	Number of N-13 remaining	Formula
Start $n = 0$	N_0	$N_0 \times \left(\frac{1}{2}\right)^0$
After 1 half-life	$N_0 \times \frac{1}{2}$	$N_0 \times \left(\frac{1}{2}\right)^1$
After 2 half-lives	$N_0 \times \frac{1}{2} \times \frac{1}{2}$	$N_0 \times \left(\frac{1}{2}\right)^2$
After 3 half-lives	$N_0 \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2}$	$N_0 \times \left(\frac{1}{2}\right)^3$
After n half-lives	$N_0 \times \frac{1}{2} \times \frac{1}{2} \ldots n$ times	$N_0 \times \left(\frac{1}{2}\right)^n$ or $N_0\left(\frac{1}{2}\right)^n$

In general, we can say that:

$$N = N_0\left(\frac{1}{2}\right)^n$$

where n = number of half-lives. This is calculated by:

$$n = \frac{\text{time elapsed}}{\text{half-life}}$$

or

$$n = \frac{t}{t_{\frac{1}{2}}}$$

Note: times must be in the same unit (seconds, minutes, years, etc.)

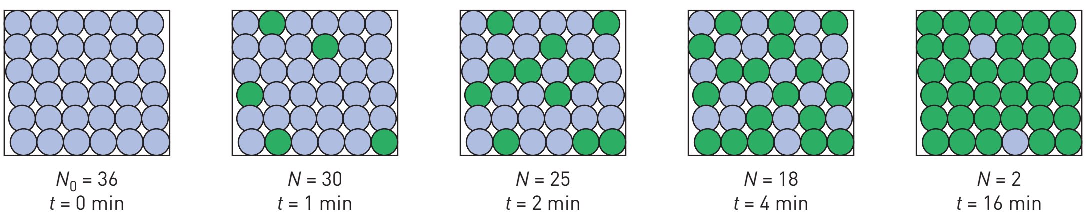

FIGURE 2 A lump of 36 atoms of thallium-206 (purple) slowly decays to lead-206 (green). After 4 minutes, only half the original 36 atoms of thallium are left. We say that thallium-206 has a half-life of 4 minutes.

Examples of some common half-lives

There is a big range of possible half-lives, as shown in Table 3. Half-lives can be very short, such as those measured in millionths of a second, or very long, such as for lead, which would last billions of years. The humble proton is believed to have a half-life of 10^{31} years – that is a 1 with 31 zeros after it.

TABLE 3 Half-lives can be very short or very long

Nuclide	Decay	Half-life
^{206}Pb	stable	infinite
^{238}U	α	4.47 billion years
^{234}Th	β^-, γ	24.1 days
^{222}Rn	α	3.82 days
^{218}Po	α	3.05 min
^{214}Po	α	1.64×10^{-4} s
^{1}H proton	γ	10^{31} years
^{1}n neutron	β^+	10.2 min

WORKED EXAMPLE 5.5A

Iodine-131 has a half-life of 8 days and undergoes beta negative decay according to the equation ${}^{131}_{53}\text{I} \rightarrow {}^{131}_{54}\text{Xe} + {}^{0}_{-1}\text{e} + \bar{\nu}_e$.

If a milk sample contains 3.0×10^{18} atoms of I-131 at a particular time, calculate the number of atoms of I-131 present after:

a 5 half-lives (40 days)

b 60 days

c 2 years.

SOLUTION

a $t_{\frac{1}{2}} = 8$ days, $N_0 = 3.0 \times 10^{18}$, $n = 5$ half-lives

$$N = N_0\left(\frac{1}{2}\right)^n$$
$$= 3.0 \times 10^{18}\left(\frac{1}{2}\right)^5$$
$$= 3.0 \times 10^{18} \times 0.03125$$
$$= 9.4 \times 10^{16} \text{ atoms (2 sf)}$$

b Number of half-lives elapsed: $n = \frac{t}{t_{\frac{1}{2}}} = \frac{60}{8} = 7.5$

$$N = N_0\left(\frac{1}{2}\right)^n$$
$$= 3.0 \times 10^{18}\left(\frac{1}{2}\right)^{7.5}$$
$$= 1.7 \times 10^{16} \text{ atoms (2 sf)}$$

c Number of half-lives elapsed: $n = \frac{t}{t_{\frac{1}{2}}} = \frac{2 \times 365}{8} = 91.25$

$$N = N_0\left(\frac{1}{2}\right)^n$$
$$= 3.0 \times 10^{18}\left(\frac{1}{2}\right)^{91.25}$$
$$= 1.0 \times 10^{-9} \text{ atoms (2 sf)}$$

This is less than 1 atom, so is clearly impossible. It is likely that the last atom of I-131 disappeared long before this.

WORKED EXAMPLE 5.5B

Iodine-131 has a half-life of 8 days. If a sample contains 3.0×10^{18} atoms of I-131 at a particular time, calculate the time that would have elapsed for there to be 1 million atoms (1.0×10^6 atoms) of I-131 left.

SOLUTION

$$N = N_0\left(\frac{1}{2}\right)^n$$
$$1.0 \times 10^6 = 3 \times 10^{18}\left(\frac{1}{2}\right)^n$$
$$\frac{1.0 \times 10^6}{3.0 \times 10^{18}} = \left(\frac{1}{2}\right)^n$$
$$3.333 \times 10^{-13} = \left(\frac{1}{2}\right)^n$$

There are two ways to solve the equation from here.

Method 1 (if your calculator can evaluate $\log_y x$):

Rearrange original formula using: $y = a^x \Leftrightarrow \log_a y = x$

$$N = N_o\left(\frac{1}{2}\right)^n \Leftrightarrow n = \log_{\frac{1}{2}}\left(\frac{N}{N_0}\right)$$

$$n = \log_{\frac{1}{2}}\left(\frac{1.0 \times 10^6}{3.0 \times 10^{18}}\right)$$

$$= 41.45 \text{ half-lives}$$

$$t = n \times t_{\frac{1}{2}} = 41.45 \text{ half-lives} \times 8 \text{ days per half-life}$$

$$= 332 = 330 \text{ days (2 sf)}$$

Method 2:

Take natural logs (ln) of both sides:

$$3.333 \times 10^{-13} = \left(\frac{1}{2}\right)^n$$

$$\ln(3.333 \times 10^{-13}) = \ln\left(\frac{1}{2}\right)^n$$

$$\ln(3.333 \times 10^{-13}) = n \times \ln\left(\frac{1}{2}\right)$$

$$-28.73 = n \times -0.693$$

$$n = \frac{-28.73}{-0.693} = 41.45 \text{ half-lives}$$

$$t = n \times t_{\frac{1}{2}} = 41.45 \text{ half-lives} \times 8 \text{ days per half-life}$$

$$= 332 = 330 \text{ days (2 sf)}$$

Note: instead of specifying N and N_0 as meaning the number of atoms, it could also mean the mass of the nuclide in a specimen. The formula still works.

CHECK YOUR LEARNING 5.5

Describe and explain

1 **Explain** what is meant by decay rate.

Apply, analyse and interpret

2 **Determine** the value for 'number of nuclei remaining' (vertical axis) by interpolating the graph of N-13 decay in Figure 1 (p. 172) at times of:

a 3 minutes

b 25 minutes.

3 **Calculate** how many grams of Rn-222 would be left in a sample after 2 weeks if there was 1.15 g at the start. Consult the half-lives listed in Table 3 (p. 173).

4 **Calculate** how much U-235 would be present on Earth for every 100 units of U-238 that was present when Earth when it was formed 4.54 billion years ago. The half-life of U-238 is 4.47×10^9 years (4.47 billion years).

5 Iodine-131 has a half-life of 8 days. If a sample contains 3.0×10^{18} atoms of I-131 at a particular time, **calculate** the time that would have elapsed for there to be 1 atom of I-131 left.

6 A phosphorus-32 sample in a lab contains 5.6 mg of the radioactive isotope. Its half-life is 14.268 days. After some time, it is analysed and found to contain 1.2 mg of P-32. **Determine** how many days would have elapsed between these readings.

Evaluate, investigate and communicate

7 **Evaluate** this statement with reasoned evidence: 'The bigger the atom, the longer the half-life'.

8 A lab technician has a sample of radioactive phosphorus but is unsure which isotope is present. She believes it to be P-30. She measures the amount and finds there is 3.70 mg present. She then waits exactly 7 days to measure it again and finds there is only 2.63 mg present now.

a **Calculate** the isotope's half-life.

b By consulting a table of half-lives, **evaluate** whether she was correct in predicting it was P–30.

Check your obook assess for these additional resources and more:

» Student book questions Check your learning 5.5

» Increase your knowledge Disintegration energy

» Weblink Decay

» Weblink Half-life

5.6 Laws of radioactive decay

KEY IDEAS

In this section, you will learn about:

+ solving radioactive decay problems involving half-lives.

Several laws and mathematical relationships have been developed for radioactivity. It was Rutherford in 1919 who first suggested that radioactive decay was an exponential process. His work underpins most of the laws we have today. This topic is an extension of the basic law of radioactive decay.

The activity law

In the previous topic, the decay of N-13 atom was discussed. At the start, the sample of 10 000 atoms was undergoing 12 decays (or disintegrations) per second (12 Bq). After 10 minutes its decay rate had dropped to 6 per second, and after a further 10 minutes its decay rate had dropped to just 3 per second (Table 1).

TABLE 1 Decay rate of N-13 over time

Time elapsed (minutes)	Number of radioactive atoms remaining, *N*	Decay rate (Activity), *A* (Bq)
0	10 000	12
10	5000	6
20	2500	3
30	1250	1.5

The **decay rate** is also called **activity** and is measured in the units called **becquerel** – named after Henri Becquerel who, as we saw at the start of the chapter, discovered the phenomenon we call radioactivity. The symbol is Bq, so 1 Bq = 1 decay (or disintegration) per second (1 dps or s^{-1}). In less active substances, the activity (A) may be expressed as disintegrations per minute (dpm).

Inspection of the data in Table 1 shows that the activity is directly proportional to the number of radioactive atoms remaining in the sample:

$$A \propto N$$

or, by replacing the proportional sign with an equals sign and a constant:

$$A = \lambda N$$

The constant, λ, is called the **decay constant**. It has the same unit as the unit of the activity. If activity is in Bq (that is, s^{-1}), then the decay constant will also have the same unit (s^{-1}). For 'years', we use the symbol y.

FIGURE 1 The radioactivity of materials is important for knowing if safety signage is needed.

decay rate
the rate of the disintegration of radioactive material generally accompanied by the emission of particles and/or gamma radiation. Also known as activity

activity
the average number of disintegrations of a radioactive nuclide per second (symbol, A; unit, becquerel; unit symbol (Bq))

becquerel
the SI unit of radioactivity, corresponding to 1 disintegration per second

decay constant
the fraction of the number of atoms that decay in 1 second

WORKED EXAMPLE 5.6A

Calculate the decay constant for the data in Table 1.

SOLUTION

$A = \lambda N$

$\lambda = \frac{A}{N}$

$= \frac{12\ s^{-1}}{10\,000}$

$= 1.2 \times 10^{-3}\ s^{-1}$

WORKED EXAMPLE 5.6B

Carbon-10 has a decay constant of 0.088 s^{-1}. Calculate the number of atoms of C-10 in a sample that has an activity of 20 MBq (megabecquerel).

SOLUTION

$A = 20\ \text{MBq} = 20 \times 10^6\ \text{Bq}$

$N = \frac{A}{\lambda} = \frac{20 \times 10^6}{0.088} = 2.3 \times 10^8$ atoms (2 sf)

WORKED EXAMPLE 5.6C

The decay constant of Ra-226 is $4.3 \times 10^{-4}\ y^{-1}$. Calculate the number of atoms in a sample of radium-226 that has an activity of 3.0 kBq.

SOLUTION

The decay constant is given in y^{-1} and must be converted to s^{-1} because activity is measured in s^{-1}. The activity of 3.0 kBq should be expressed as 3.0×10^3 Bq.

$\lambda = \frac{4.3 \times 10^{-4}}{1\ \text{year}} = \frac{4.3 \times 10^{-4}}{365 \times 24 \times 60 \times 60\ \text{seconds}} = 1.4 \times 10^{-11}\ s^{-1}$

$N = \frac{A}{\lambda} = \frac{3.0 \times 10^3}{1.4 \times 10^{-11}} = 2.2 \times 10^{14}$ atoms (2 sf)

Exponential decay law

A graph of the decay of a radioactive nuclide looks like exponential decay and in fact is. The decay of N-13 as presented earlier has the shape shown in Figure 2.

The general exponential decay law is written as:

$$N = N_0 e^{-kt}$$

where e is the base of the natural logarithm, k is the rate constant, and t is time elapsed. For radioactive decay, we modify the formula to:

$$N = N_0 e^{-\lambda t}$$

where the lambda (λ) is the decay constant, N_0 is the starting number of atoms (at $t = 0$), and N is the number remaining after time t

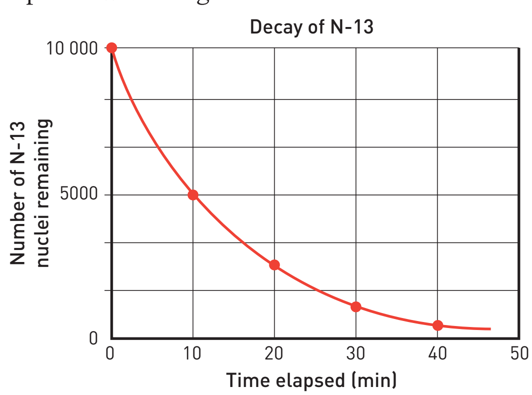

FIGURE 2 Graph of the decay of N-13 with time

Study tip

The negative in front of the exponent k in the decay law means that the value of N is getting smaller with time.

has elapsed. The relationship between the decay constant and half-life is derived in the following manner:

$$N = N_0 e^{-\lambda t}$$

Divide both sides by N_0:

$$\frac{N}{N_0} = e^{-\lambda t}$$

Take the natural logarithm ($\log_e$ or ln) of both sides:

$$\ln\left(\frac{N}{N_0}\right) = -\lambda t$$

Half-life is defined as the time in which one-half of the radioactive atoms in a sample will decay – that is, when $N = \frac{1}{2}N_0$, and we can then replace t by $t_{\frac{1}{2}}$:

$$\ln\left(\frac{\frac{1}{2}N_0}{N_0}\right) = -\lambda t_{\frac{1}{2}}$$

Cancel out the N_0 terms:

$$\ln\left(\frac{1}{2}\right) = -\lambda t_{\frac{1}{2}}$$

$$-0.693 = -\lambda t_{\frac{1}{2}}$$

$$t_{\frac{1}{2}} = \frac{0.693}{\lambda} \quad \text{or} \quad \lambda = \frac{0.693}{t_{\frac{1}{2}}}$$

WORKED EXAMPLE 5.6D

Marie Curie conducted many experiments on the radium isotope Ra-226, which has a half-life of 1600 years.

a Calculate the decay constant, λ, of Ra-226.

b In Curie's lab 120 years ago there was a sample of radium that had 1.250 mg of Ra-226 present. Calculate how much Ra-226 would be present in that sample today.

SOLUTION

a The decay constant for Ra-226 is calculated by:

$$\lambda = \frac{0.693}{t_{\frac{1}{2}}} = \frac{0.693}{1600}$$

$$= 4.3 \times 10^{-4}\ \text{y}^{-1}\ (\text{or } 0.000\,43\ \text{y}^{-1})$$

b $N = N_0 e^{-\lambda t}$

$$= 1.250 \times e^{-(0.000\,43 \times 120)}$$
$$= 1.250 \times e^{-0.0516}$$
$$= 1.250 \times 0.950$$
$$= 1.2\ \text{mg (2 sf)}$$

Answer: $N = 1.2$ mg.

Using activity in calculations

As activity is proportional to the number of atoms ($A \propto N$), we can rewrite the exponential decay law as:

$$A = A_0 e^{-\lambda t}$$

By taking natural logs of each side, this becomes:

$$\ln\frac{A}{A_o} = -\lambda t$$

Both formulas are useful when dealing with activity data.

WORKED EXAMPLE 5.6E

Actinium-228 is a beta emitter used as an agent for radiation therapy that targets cancer cells in the body. A sample used in a hospital has an activity of 315 Bq. After 18 hours, the activity has dropped to 41.4 Bq. Calculate the half-life of actinium-228.

SOLUTION

$$A = A_0 e^{-\lambda t}$$

$$\ln\frac{A}{A_0} = -\lambda t$$

$$\ln\left(\frac{41.4}{315}\right) = -\lambda \times 18$$

$$-2.03 = -\lambda \times 18$$

$$\lambda = \frac{2.03}{18} = 0.113\ \text{h}^{-1}$$

$$t_{\frac{1}{2}} = \frac{0.693}{\lambda}$$

$$= \frac{0.693}{0.113} = 6.15\ \text{hours (3 sf)}$$

Alternatively:

$$A = A_0\left(\frac{1}{2}\right)^n$$

$$n = \log_{\frac{1}{2}}\left(\frac{A}{A_0}\right)$$

$$= \log_{\frac{1}{2}}\left(\frac{41.4}{315}\right)$$

$$= 2.928\ \text{half-lives}$$

Therefore,

$$t_{\frac{1}{2}} = \frac{t}{n} = \frac{18\ \text{hours}}{2.928\ \text{half-lives}} = 6.15\ \text{hours (3 sf)}$$

CHECK YOUR LEARNING 5.6

Describe and explain

1 $^{124}_{55}Cs$ has a half-life of 31 s.

a **Calculate** the decay constant in s^{-1} and min^{-1}.

b **Calculate**, for an initial sample of 20.0 g of Cs-124, how much will be left (in grams) after:

i 62 s

ii 124 s

iii 10 minutes.

2 $^{68}_{32}Ge$ has a half-life of 9.0 minutes. **Calculate** how many minutes will it take for the germanium in a 1.00 g sample to decay to 1.00 mg.

3 Use the data in Table 2 to work out the relationship between distance and activity (**sketch** a graph, linearise it and **calculate** the equation of a line of best fit).

TABLE 2

Distance, *d* (mm)	4	6	8	14	20	30	40
Activity, *A* (dpm)	11 266	5046	2956	638	230	152	136

Check your obook assess for these additional resources and more:

» Student book questions
Check your learning 5.6

» Video
Activity vs Distance

» Video
Half-life with dice

» Video worksheet
Activity vs Distance
Half-life with dice

SCIENCE AS A HUMAN ENDEAVOUR

5.7 Radiometric dating of materials

KEY IDEAS

In this section, you will learn about:

+ how knowledge of radioactive decay enables radiometric dating of materials.

A key use of radioactivity is for determining the age of ancient samples of rocks, plant and animal tissue. This is called radiometric dating ('metric' means *to measure*). There are many methods for doing this.

Uranium decay

The universe is believed to be somewhere between 13 billion and 15 billion years old. Our Earth has been around for over 4 billion (4×10^9) of those years. Grains of the mineral zircon from gneiss rocks have been measured as being 3.962 billion years old, with a margin of error of 3 million years.

This estimate is based on the belief that small amounts of radioactive uranium-238 were trapped in the zircon at the time of crystallisation. Since then, the uranium has gradually been decaying, eventually changing into stable lead. The age calculation is done by measuring the amounts of lead and uranium trapped in the rock. By knowing the half-life of U-238, the age t can be calculated. Some other isotopes used for radiometric dating of rocks are shown in Table 1.

TABLE 1 Various methods used to measure the age of rocks

Parent		Daughter	$t_{\frac{1}{2}}$ (years)	Main source	Range (years)
K-40	→	Ar-40	1.3 billion	mica and feldspar	100 000 to 4.5 billion
Th-232	→	Pb-208	14 billion	zircon and uranium ore	10 million to 4.5 billion
U-238	→	Pb-206	4.5 billion	zircon and uranium ore	10 million to 4.6 billion

Scientists are sometimes challenged as to the accuracy of their age estimates. To ensure the dating is reliable, they take a number of quality control steps. These include taking duplicate samples and having them tested in independent laboratories, verifying by comparing to other non-radiometric methods, and cross-checking with other radiometric pairs (such as Th–Pb compared to K–Ar). Scientists are also aware that there can be laboratory errors, unrecognised geologic factors, contamination of the sample or misapplication of techniques. These all must be taken into consideration for a reliable test.

Radiocarbon dating

The age of any object made from previously living material, such as wood, can be estimated using radiocarbon dating. All living plants take in and excrete carbon dioxide. The vast majority of the carbon atoms are present as the isotope C-12, but a very small fraction (about 1.35×10^{-12}:1) are the radioactive isotope C-14. This level is commonly described as 1.35 ppt, meaning 'parts per trillion' (10^{-12}). This ratio (R_0) has remained constant for thousands of years because, even though C-14 decays (with a half-life of 5730 years), more is being made by the cosmic radiation from space bombarding nitrogen in the atmosphere:

$$^{14}_{7}N + ^{1}_{0}n \rightarrow ^{14}_{6}C + ^{1}_{1}H$$

When plants and animals die, they stop exchanging C-14 with the atmosphere so the C-14 decays without being replaced. As a result, the C-14:C-12 ratio drops. This is labelled as R_t.

After 5730 years, it would be half the normal (living) ratio. If the ratio can be determined, then the time that has elapsed since death can be established. You can use any half-life formula to determine the time that has elapsed. In place of the values for initial and final activity, number of particles or mass, you can just use the initial and final ratios.

Study tip

Some worked examples demonstrating the radiocarbon dating calculation can be found on your obook assess.

Single-grain optically stimulated luminescence (OSL)

Whereas organic deposits can be dated using radiocarbon techniques, minerals (such as quartz sand) have no carbon and so require a different method. A recent method for dating minerals uses single-grain optically stimulated luminescence (OSL). OSL dating gives an estimate of the time since mineral grains were last exposed to sunlight.

Scientists applied this method to individual grains of quartz from Madjedbebe near Kakadu National Park in the Northern Territory and found that it was settled around 65 000 years ago. This sets a new minimum age for the human colonisation of Australia and the dispersal of modern humans out of Africa and across south Asia. Radiocarbon dating is only useful for specimens that were previously living. It has a limit of about 50 000 years. Single-grain OSL dating provides a means of determining the burial ages of non-living artefacts and can measure back from 100 to 350 000 years ago.

The time that has elapsed since mineral grains were last exposed to sunlight can be determined from measurements of the OSL signal together with determinations of the radioactivity of the sample and the material surrounding the environmental dose rate. The burial time of the grains in calendar years before present can then be calculated.

FIGURE 1 The Madjedbebe rock shelter site during the excavation

CHECK YOUR LEARNING 5.7

Apply, analyse and interpret

1 A piece of wood from a giant redwood tree has a C-14 ratio only one-quarter of that found in living tissue. **Determine** the age of the wood.

Investigate, evaluate and communicate

2 For hundreds of years, the Shroud of Turin had been claimed to be the burial garment of Jesus. Recently, a sample was analysed and found to have a C-14 count of 92% of that found in living tissue.

a **Calculate** the age of the shroud.

b **Propose** what may be controversial about the answer.

c **Determine** the amount of C-14 as a percentage of the C-14 in living tissue if it really was from Jesus's time.

Check your obook assess for these additional resources and more:

- » Student book questions
  Check your learning 5.7
- » Increase your knowledge
  Worked examples demonstrating radiocarbon dating calculations
- » Weblink
  Radiocarbon dating
- » Weblink
  Dating techniques

CHAPTER 5

Review

Summary

5.2

- Any radiation that can remove an electron from an atom and create a heavy positive ion and free electron is termed an ionising radiation.
- Ionising radiations include electromagnetic radiation (gamma rays, X-rays and far-ultraviolet radiation) as well as energetic particles such as alpha and beta particles.

5.3

- Radioactivity (also known as radioactive decay) is the process whereby atoms emit particles or rays of high energy from their nuclei. The original unstable parent nucleus decays to form a daughter nucleus and at least one other particle.
- In balancing decay equations, the sum of the atomic mass numbers on the left of the equation must be the same as the sum of the atomic mass numbers on the right. The total charge on the left side of the equation must equal the total charge on the right side. The number of protons determines the name and symbol of the element.

5.4

- Three types of decay are associated with three unstable states of a nuclide: too many neutrons (beta negative decay), too many protons (beta positive decay), and too many protons and neutrons (alpha decay).
- The half-life of a radioactive isotope is the time taken for half the radioactive atoms in a sample to decay.
- A chain of radioactive decay is called a decay series and it continues until a stable nuclide is formed.

5.6

- The rate at which a radioactive nuclide decays is called its activity (A). The unit for activity is the becquerel (Bq), and it will decrease exponentially with time.
- The measured activity or intensity of a nuclide decreases in an inverse-squared relationship with distance.
- The measured activity or intensity of a nuclide decreases exponentially with thickness of the shielding material.

Key terms

- activity
- alpha decay
- alpha radiation
- antineutrino
- antiparticle
- becquerel
- beta negative decay
- beta negative radiation
- beta positive decay
- beta positive radiation
- decay constant
- decay rate
- decay series
- gamma decay
- gamma radiation
- half-life
- ionising radiation
- neutrino
- nuclear radiation
- positron

Key formulas

Half-life	$N = N_0\left(\frac{1}{2}\right)^n$

Revision questions

The relative difficulty of these questions is indicated by the number of stars beside each question number: ★ = low; ★★ = medium; ★★★ = high.

Multiple-choice

1 A positron is an atomic particle that has:

A the mass of an electron and the charge of a proton.

B the mass of an electron and the charge of a neutron.

C the mass of a neutron and the charge of a proton.

D the mass of a proton and the charge of an electron.

2 A certain radioactive element has a half-life of 20 d. The time it will take for $\frac{7}{8}$ of the atoms originally present to disintergrate is:

A 20 d

B 40 d

C 60 d

D 80 d

3 Which one of these nuclear reactions is possible?

A $^{10}_{5}B + ^{4}_{2}He \rightarrow ^{13}_{7}N + ^{1}_{1}H$

B $^{14}_{7}N + ^{1}_{1}H \rightarrow ^{12}_{6}C + \beta^{-} + \nu$

C $^{10}_{5}B + ^{1}_{0}n \rightarrow ^{11}_{5}B + \beta^{-} + n$

D $^{23}_{11}Na + ^{1}_{1}H \rightarrow ^{20}_{10}Ne + ^{4}_{2}He$

4 What are the numbers of protons *Z* and neutrons *N* in the missing fragment (shown by the question mark) of the following fission reaction?

$^{235}_{92}U + ^{1}_{0}n \rightarrow ? + ^{140}_{55}Cs + 4^{1}_{0}n$

A $Z = 55$ and $N = 37$

B $Z = 37$ and $N = 55$

C $Z = 92$ and $N = 37$

D $Z = 37$ and $N = 92$

5 Which one of the following particles is always associated with beta negative decay?

A gamma particle

B electron neutrino

C antielectron neutrino

D electron antineutrino

Short answer

Describe and explain

★ 6 **Define**: alpha radiation, antiparticle, beta negative radiation, beta positive radiation, gamma radiation, half-life.

★ 7 **Explain** whether isotopes of a particular substance have the same properties.

★ 8 Iridium-192 is used in the treatment of early breast cancer. It has a half-life of 74 days. **Calculate** the time required for 3.6 mg of an iridium-192 to decay to:

a 0.90 mg

b 0.25 mg.

★ 9 **Identify** the missing symbols in the following equations:

a $^{234}_{91}Pa \rightarrow ^{234}_{92}U + ?$

b $^{?}_{?}Rn \rightarrow ^{218}_{84}Po + a$

★★ 10 **Explain** whether C-14 dating can be used to measure the age of stone walls and tablets of ancient civilisations.

★★ 11 Carbon-14 was used to date a medieval linen sample. **Calculate** how old it was if it had a C-14 : C-12 ratio that was only 89.7% of the expected living tissue ratio.

★★ 12 Some rocks in your neighbourhood show that their percentage of uranium-236 is 67% of what you expected. **Calculate** the age of the rocks give that $t_{\frac{1}{2}}$ for U-236 is 2.39×10^{7} years.

Apply, analyse and interpret

★ 13 **Determine** the name of the element and the number of protons and neutrons in:

a Pu-244

b Lr-260

c Po-209

d $^{141}_{59}Pr$

★★ 14 The age of an ice sheet in Antarctica is to be determined by examining a meteorite that is embedded in the ice sheet. It is shown that the meteorite that is 'freshly fallen' will have radioactive decay of $^{26}_{13}Al$ nuclides at a rate of 11.4 Bq per kg. **Determine** the age of the ice sheet in years given that the half-life of $^{26}_{13}Al$ is 7.3×10^{5} years.

★★ **15** **Determine** what elements are formed by the radioactive decay shown in each of the following:

a $^{24}_{11}Na\ (\beta^-)$

b $^{22}_{11}Na\ (\beta^+)$

c $^{210}_{84}Po\ (\alpha)$

d $^{32}_{15}P\ (\beta^-)$

★★ **16** **Interpret** the information that a certain nuclide, represented by $^{b}_{a}X$, ejects an alpha particle followed by an emission of a beta particle. Use *Y* and *Z* as daughter symbols.

★★ **17** **Determine** the missing nuclides in the following nuclear equations:

a $^{11}_{5}B + ^{4}_{2}He \rightarrow ^{14}_{7}N + ?$

b $^{23}_{11}Na + ^{1}_{0}n \rightarrow ?$

c $^{27}_{13}Al + ^{2}_{1}H \rightarrow ^{4}_{2}He + ?$

d $? + ^{4}_{2}He \rightarrow ^{42}_{20}Ca + ^{1}_{1}H$

e $? + ^{1}_{0}n \rightarrow ^{27}_{12}Mg + ^{1}_{1}H$

f $? + ^{4}_{2}He \rightarrow ^{12}_{6}C + ^{1}_{0}n$

★★ **18** **Determine** the symbols for two new heavy nuclides from these incomplete equations:

$^{249}_{98}Cf + ^{12}_{6}C \rightarrow 4^{1}_{0}n + ?$

$^{242}_{94}Pu + ^{22}_{10}Ne \rightarrow 4^{1}_{0}n + ?$

★★ **19** **Deduce** the stable nuclide formed when the fission fragment Sr-96 undergoes four successive β^- emissions before a stable nucleus is formed.

★★★ **20** The half-life of a cobalt-60 source used for food irradiation is 5.26 years.

a If the original sample has 3.5×10^{24} atoms of Co-60, **determine** how many atoms will be left after 2 years.

b If it is not safe for disposal until the amount of radioactive isotope is less than one-thousandth of its original amount, **calculate** how many years this is.

★★★ **21** Iodine-131, used for destroying malignant tumours of the thyroid, has a half-life of 8.07 days.

a If it has 5×10^{22} atoms of I-131, **determine** how many days will elapse before it has 5×10^{20} atoms.

b **Calculate** how much time will elapse before there are a dozen atoms left.

Investigate, evaluate and communicate

★★ **22** **Devise** a procedure to measure the half-life of U-234 when it is known to be 4.51 billion years.

★★ **23** **Develop** an equation for the likely first decay of the following nuclides based on the description of the nuclide following it:

a $^{38}_{20}Ca$ (too many protons)

b $^{35}_{15}P$ (too many neutrons)

c $^{12}_{6}C$ (on the line of stability)

★★ **24** The U-238 present on Earth was created in a supernova 10 billion years ago. Imagine you were observing it in a lab and suddenly one of the atoms decayed and gave off an alpha particle. **Propose** why it would suddenly do this after so long, and **deduce** what may have triggered it.

★★★ **25** **Design** an experiment involving radiation to measure how much liquid is in a can without opening it. Hint: alpha radiation would not be suitable for this experiment. Why not?

★★★ **26** **Assess** the following data in which the number of atoms of a sample of a beta-emitting phosphorus nuclide was measured as a function of time. The results are shown in Table 1.

TABLE 1

Time elapsed (h)	Number of atoms (*N*)
0.0	36 506
0.5	31 501
0.75	29 268
1.0	27 106
2.0	20 244
5.0	8 256
10.0	1 913
13.0	800
18.0	181

a **Construct** a graph of *N* vs *t* and estimate the half-life of the sample.

b **Sketch** ln(*N*) vs *t* for this data and determine the half-life of the phosphorus. Hint: the gradient of an ln(N) vs t graph is the negative of the decay constant ($-\lambda$).

★★★ **27** The following data were collected at the same time each school day (Table 2).

Note: To measure the activity of the sample the time was measured for 2000 counts. You will also need to subtract the background radiation of 0.217 Bq.

TABLE 2

Day	Time for 2000 counts
Mon	1 min 16 s
Tues	1 min 39 s
Wed	2 min 10 s
Thu	2 min 51 s
Fri	3 min 40 s
Mon	8 min 28 s
Tue	10 min 15 s
Wed	13 min 48 s
Thu	17 min 33 s
Fri	22 min 59 s

a **Calculate** the observed activity and then the actual activity by subtracting background activity.

b **Calculate** the half-life by a graphical method. Hint: watch the 'time elapsed' – there are some days when no data was taken (who would go to school at the weekend?).

c **Evaluate** the results of the experiment to determine the half-life of a sample of a radioactive nuclide undergoing beta decay.

★★★ **28** **Examine** the following data for a radioactive nuclide, which was collected over a period of a week.

The mass of the isotope was measured every day to determine its half-life. The mass is expressed in micrograms (μg). The experimental results are shown in Table 3.

TABLE 3

t (day)	0	1	2	3	4	5	6	7
m (μg)	10 000	7680	5830	4440	3446	2586	1954	1490

a **Estimate** the half-life of the radioactive nuclide by inspection (no calculations).

b **Calculate** the percentage error in the experimental results given that the isotope's accepted half-life is 2.6 days.

c **Sketch** ln(*N*) against time and determine its half-life graphically. Hint: the gradient of ln(*N*) vs *t* graph equals the negative of the decay constant ($-\lambda$)

★★★ **29** The radioactive isotope Kr-88 undergoes β^- decay. The activity of the isotope was measured every 30 minutes as shown in Table 4.

TABLE 4

t (minutes)	0	30	60	90	120
A (Bq)	352	312	276	244	208

a **Estimate** the half-life by inspection (no calculations).

b **Determine** the experimental half-life by whatever means you choose (graphing in *A* vs *t*, or by using the exponential decay formula).

c **Determine** the percentage error in the experimental results, given the accepted value of the half-life is 2.84 hours.

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CHAPTER 6

Nuclear energy

Uranium can be extracted and concentrated for use in a nuclear reactor where it is 'transmuted' into other substances in an artificial nuclear reaction. These artificial transmutations are the subject of this chapter.

OBJECTIVES

→ Define artificial transmutation.
→ Distinguish between artificial transmutations and natural radioactive decay.
→ Define nuclear fission.
→ Explain a neutron-induced nuclear fission reaction, including references to extra neutrons produced from many of these reactions.
→ Research nuclear safety, considering the suitability of using the sources of information in terms of their credibility.
→ Explain a fission chain reaction.
→ Define nuclear fusion.
→ Define mass defect, binding energy and binding energy per nucleon.
→ Recall Einstein's mass–energy equivalence relationship.
→ Solve problems involving Einstein's mass–energy equivalence relationship.
→ Explain that more energy is released per nucleon in nuclear fusion than in nuclear fission because a greater percentage of the mass is transformed into energy.

Source: *Physics 2019 v1.2 General Senior Syllabus Queensland Curriculum & Assessment Authority*

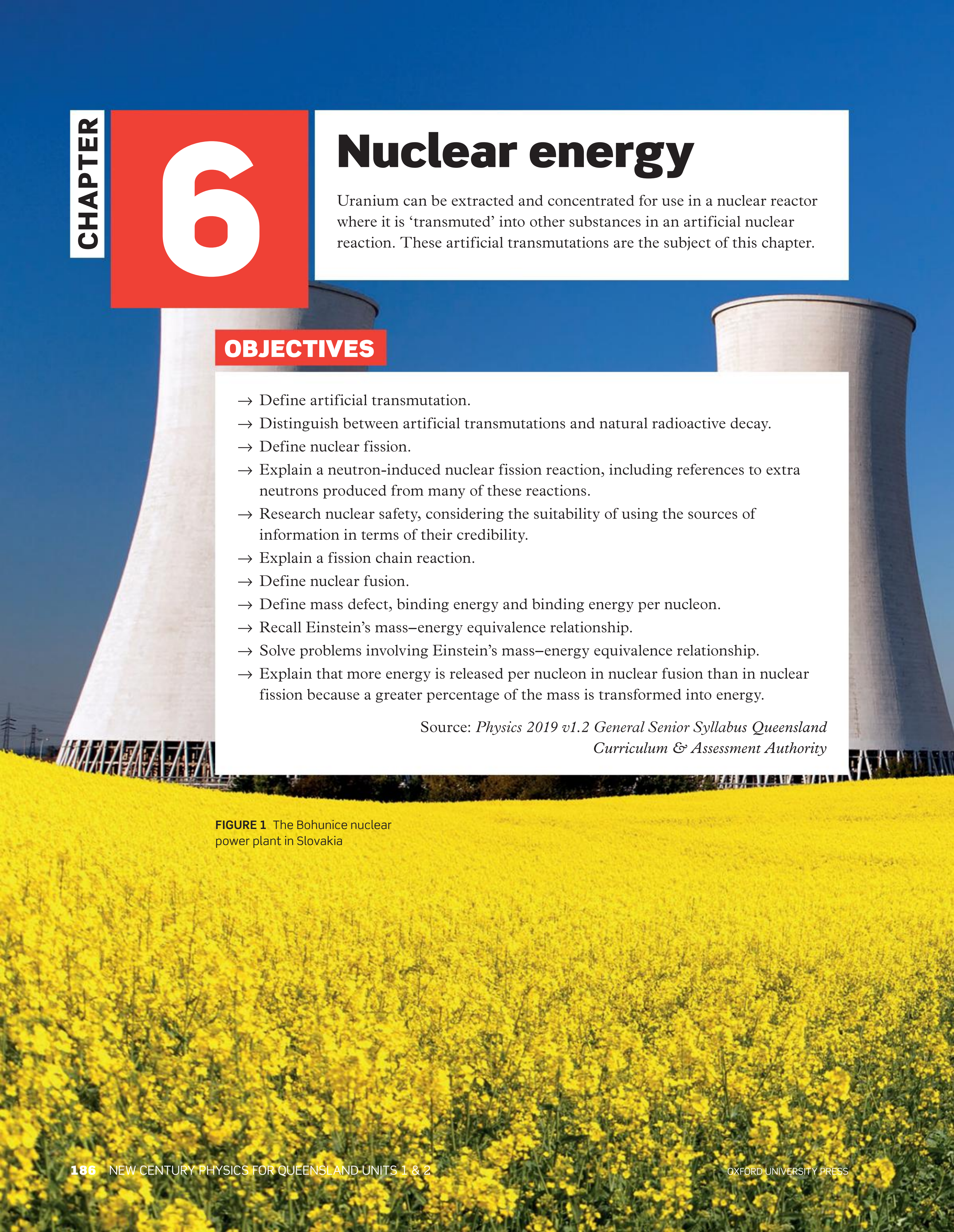
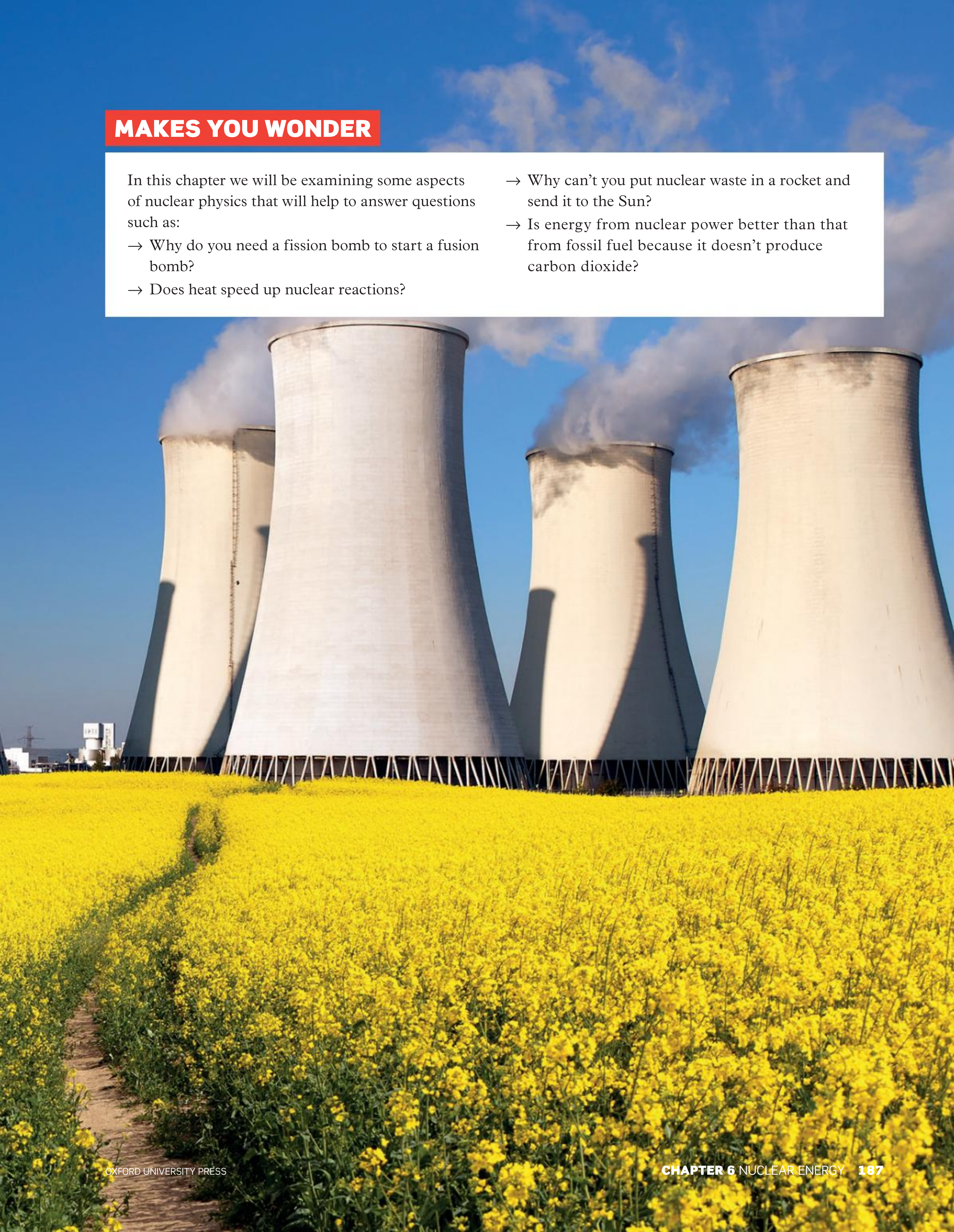


FIGURE 1 The Bohunice nuclear power plant in Slovakia



MAKES YOU WONDER

In this chapter we will be examining some aspects of nuclear physics that will help to answer questions such as:

→ Why do you need a fission bomb to start a fusion bomb?

→ Does heat speed up nuclear reactions?

→ Why can't you put nuclear waste in a rocket and send it to the Sun?

→ Is energy from nuclear power better than that from fossil fuel because it doesn't produce carbon dioxide?

6.1 Artificial transmutation

KEY IDEAS

In this section, you will learn about:

+ artificial transmutations including proton, alpha, deuteron and neutron bombardment.

nuclear reaction a reaction, as in fission, fusion or radioactive decay, that alters the energy, composition or structure of an atomic nucleus

artificial transmutation a nuclear reaction induced artificially by means of bombardment with some fundamental particles

Nuclear reactions can be classified as either due to natural radioactive decay or artificial nuclear reactions. The radioactive decay processes discussed in Chapter 5 are examples of spontaneous or 'natural' nuclear reactions. They occur naturally by themselves, with no external influence or particles required. Other nuclear reactions can be induced artificially using **artificial transmutation**.

Artificial transmutation

Artificial transmutation involves bombarding a nucleus with a projectile, such as a proton $^{1}_{1}p$ or $^{1}_{1}H$, an alpha particle $^{4}_{2}He$, a deuteron $^{2}_{1}H$, a neutron $^{1}_{0}n$, or other small nuclei such as $^{12}_{6}C$, $^{15}_{7}N$ or $^{16}_{8}O$.

Proton bombardment

Firing a proton at a stable nucleus can cause the nucleus to split in two. For example, a lithium atom is very stable so it doesn't decay naturally, but when a proton is fired at lithium it transmutes into two helium nuclei (alpha particles) with a flash of gamma energy:

$$^{1}_{1}p + ^{7}_{3}Li \rightarrow ^{4}_{2}He + ^{4}_{2}He + \gamma$$

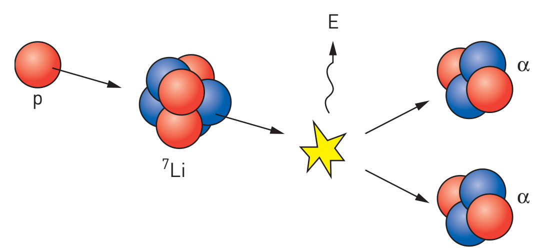


FIGURE 1 Proton bombardment of a Li-7 nucleus

Alpha bombardment

In 1919, after the proton had been discovered, Rutherford designed a series of experiments to probe further into the production of the proton. He bombarded nitrogen gas with 'bullets' of alpha particles:

$$^{4}_{2}He + ^{14}_{7}N \rightarrow ^{17}_{8}O + ^{1}_{1}p$$

The equation shows that the artificial transmutation of nitrogen into oxygen had occurred. Rutherford also found that when fast, high-energy alpha particles were used, neutrons were sometimes formed. For example, when beryllium nuclei are bombarded with high-energy alpha particles, carbon nuclei and fast-moving neutrons are produced:

$$^{4}_{2}He + ^{9}_{4}Be \rightarrow ^{12}_{6}C + ^{1}_{0}n$$

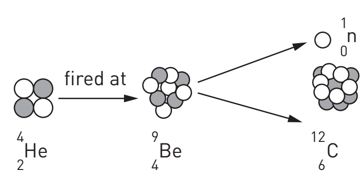


FIGURE 2 Bombardment of a beryllium nucleus by high-energy alpha particle 'bullets'

Deuteron bombardment

Although it is almost impossible to turn lead into gold, **deuterons** ($^{2}_{1}H$) can be used to make gold from mercury or platinum:

deuterons the nuclei of deuterium atoms, each consisting of a proton and a neutron

$$^{2}_{1}H + ^{199}_{80}Hg \rightarrow ^{197}_{79}Au + ^{4}_{2}He$$

$$^{2}_{1}H + ^{196}_{78}Pt \rightarrow ^{197}_{79}Au + ^{1}_{0}n$$

For both of these reactions, the deuterons must be given a high enough speed by a suitable accelerator that they can enter the nuclei of the target atoms. It is expensive to use such an accelerator, so it is cheaper to mine gold.

Neutron bombardment

Another common way of producing artificial transmutation is by using neutrons as the bombarding particles. Because they carry no charge, neutrons can enter the nuclei of the target atoms more easily than charged particles can. The target is said to have 'captured' the neutron. Some examples of transmutations caused by neutron bombardment and capture are:

$$^{10}_{5}B + ^{1}_{0}n \rightarrow ^{7}_{3}Li + ^{4}_{2}He$$

$$^{238}_{92}U + ^{1}_{0}n \rightarrow ^{239}_{92}U$$

$$^{59}_{27}Co + ^{1}_{0}n \rightarrow ^{60}_{27}Co$$

The Co-60 produced in the last reaction decays spontaneously by β^- and γ emission to stable Ni-60. An electron antineutrino is also produced, as it is with all β^- decay:

$$^{60}_{27}Co \rightarrow ^{60}_{28}Ni + ^{0}_{-1}e + \bar{\nu}_e + \gamma$$

Cobalt-60 is used as the gamma source for school radioactive specimens. By completely encasing the radioactive sample in plastic, the beta negative particles are absorbed whereas the gamma rays can penetrate through it.

CHECK YOUR LEARNING 6.1

Describe and explain

1 **Identify** the names of these bombarding particles: $^{4}_{2}He$, $^{1}_{1}H$, $^{1}_{1}p$, $^{2}_{1}H$, $^{1}_{0}n$.

2 **Define** artificial transmutation.

Apply, analyse and interpret

3 **Deduce** the product of this proton bombardment reaction: $^{31}_{15}P + ^{1}_{1}H \rightarrow ^{1}_{0}n + ?$

4 Create balanced equations of the following reactions and **determine** what type of bombardment each is:

a $^{6}_{3}Li + ^{2}_{1}H \rightarrow ^{1}_{1}H + ?$

b $^{27}_{13}Al + ? \rightarrow ^{27}_{12}Mg + ^{1}_{1}H$

Investigate, evaluate and communicate

5 **Create** a balanced equation for a reaction in which the deuteron bombardment of As-75 produces a proton and one other nuclide.

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6.2 Nuclear fission

KEY IDEAS

In this section, you will learn about:

- neutron-induced nuclear fission reactions
- Einstein's mass–energy equivalence relationship and how to solve related equations
- fission chain reactions.

nuclear fission
a nuclear reaction in which a large unstable nucleus splits, forming two (or more) smaller, more stable nuclei and releasing neutrons and energy

nuclear fusion
a nuclear reaction in which two or more light atomic nuclei react (fuse) to form one or more different, heavier atomic nuclei and subatomic particles

Artificial nuclear reactions can be classified by the type of bombardment, but they can also be classified as either **nuclear fission** or **nuclear fusion**.

In nuclear fission, the lighter colliding particle makes the heavy parent more unstable, and it fragments or fissions (Latin *fissus* = 'cleaved' or 'split') into smaller nuclei and other particles. These smaller particles have higher binding energy per nucleon than the big nucleus. Energy is released in this fission process. Fission is more likely for atoms on the right of Fe-56 in the stability graph that was introduced in Chapter 4 (see Figure 1).

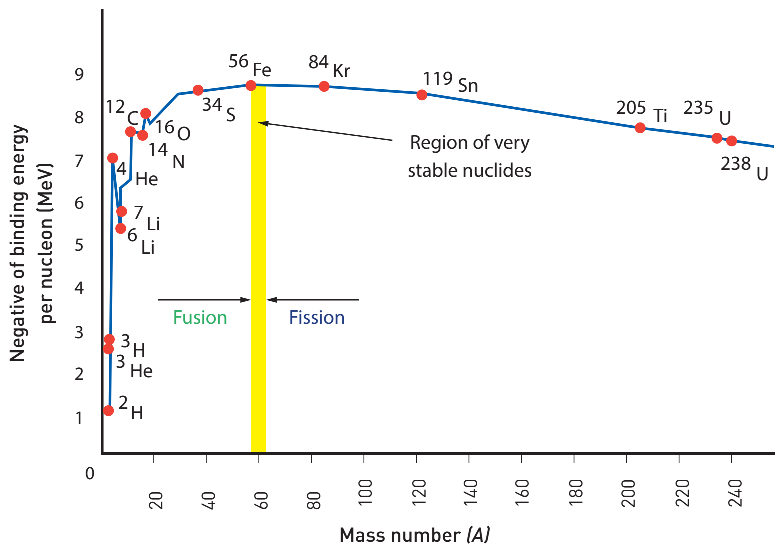

FIGURE 1 Variation in binding energy per nucleon

In nuclear fusion, the colliding particle unites with the parent and fuses (Latin *fusus* = 'melted' or 'united') into a single nucleus with a higher mass. Sometimes other small particles (n, p) are given off. The new composite nucleus is more stable than the colliding particles as its binding energy per nucleon is greater. Remember from Chapter 4 that the greater the binding energy per nucleon, the more stable a nucleus is. The stability graph peaks at Fe-56 and 'droops' either side. To the left, particles can improve their stability by fusing into a bigger nucleus. When they do fuse, they release energy.

Neutron-induced nuclear fission

The German scientists Otto Hahn and Fritz Strassmann made an amazing discovery in 1938. When U-235 was bombarded with neutrons, sometimes smaller nuclei were produced, which were approximately half the size of the original (for example, $^{136}_{56}Ba$ and $^{84}_{36}Kr$). They were baffled by this, but Lise Meitner and Otto Frisch (Jewish physicists who escaped Nazi Germany in 1938 and were working in Scandinavia) quickly realised what happened. The U-235 nucleus absorbed the neutron to form a U-236 nucleus. Then, like a drop of water, it split into two roughly equal pieces (see Figure 2). They called it 'nuclear fission' because it reminded them of biological fission (cell division). A tremendous amount of energy is released because the mass of U-235 is considerably greater than that of the fission fragments.

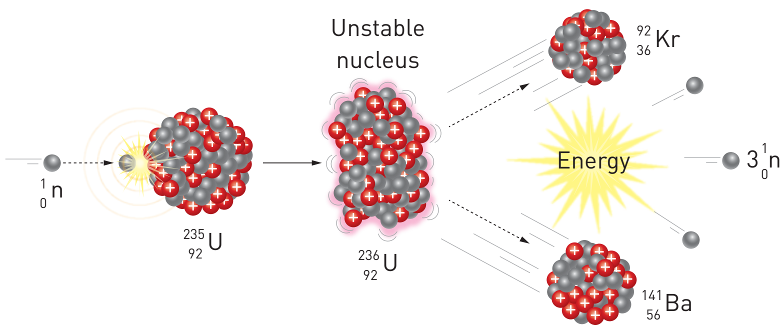

FIGURE 2 Neutron-induced nuclear fission of U-235

In early 1940, when Germany was already at war, Adolf Hitler banned the sale of uranium from the Czech mines he had overrun. American physicists were alarmed that the Germans might be developing a bomb, so the Allies began their own research in the United States. This was known as the Manhattan Project and culminated in the nuclear destruction of two Japanese cities, Hiroshima and Nagasaki, thus ending the Second World War.

To make nuclear fission work, more neutrons must be released than are consumed to produce a **chain reaction**. The released neutrons continue to react with other U nuclei, and so on. Figure 3 shows a four-generation chain reaction.

chain reaction
a series of nuclear fissions, each initiated by a neutron produced in a preceding fission

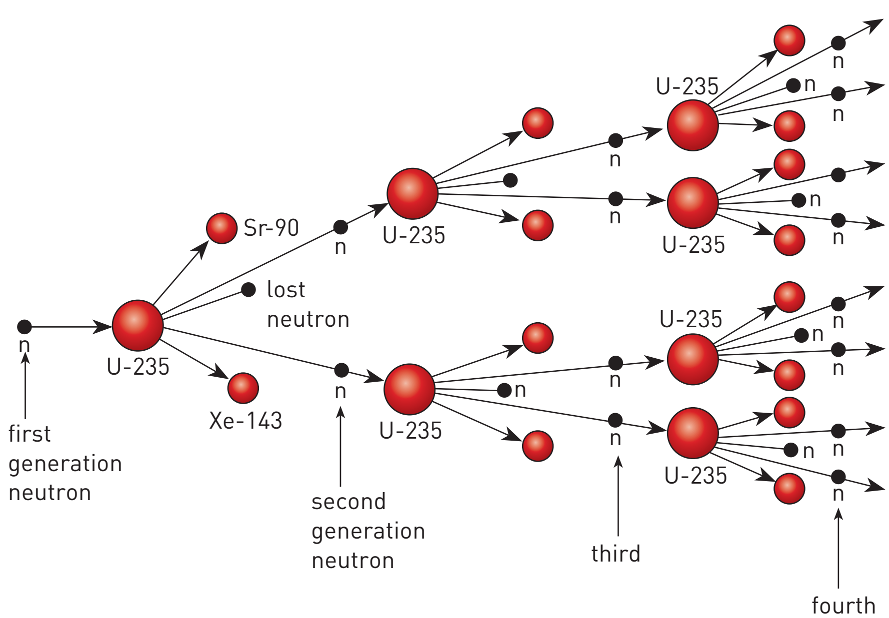

FIGURE 3 A chain reaction can occur when a neutron strikes a U-235 nucleus. However, the neutron must be travelling at the right speed and there must be a lot of U-235 present.

The liquid drop model for fission

The nucleus of an atom is a complicated body that is not fully understood. However, some of its features can be described by an idealised model. When we say 'model', we don't mean a physical object. 'Model' in this context means a representation that describes, simplifies or provides an explanation of the workings of something (in this case, a nucleus). A model is rarely the work of any one person – it usually arises from collaboration across many disciplines.

According to the liquid drop model, the atomic nucleus behaves like the molecules in a drop of liquid. In the ground state, the nucleus is spherical. Surface tension makes the surface of the drop as small as possible and it can do so by making the drop spherical. The nuclear strong force between nucleons (protons or neutrons) also draws the nucleons together. However, this spherical shape also crowds the protons together, and the charge repulsion (called the electrostatic force or Coulomb force) between protons pushes them apart. It is a balance between pushing and pulling forces – a spherical and non-spherical shape. This is where you can think of it like a wobbling drop of water.

If sufficient kinetic energy is added, such as in the arrival of a neutron, this spherical nucleus is distorted into a dumbbell shape and splits into two fragments. Since these fragments are a more stable configuration, the splitting of such heavy nuclei is accompanied by energy release.

For heavy nuclei, where the charge repulsion is big, fissioning is a way to release the strain. It also makes lighter nuclei that are less resistant to deformation so they don't fission as easily.

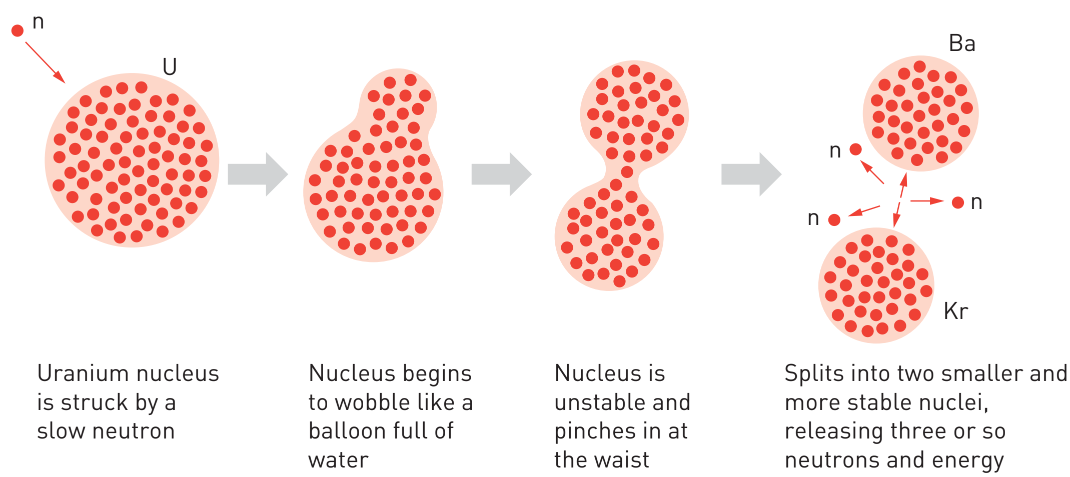

FIGURE 4 The water drop model showing the disintegration of uranium-235 by a slow neutron

In each generation, the number of fissioning nuclei increases even though some neutrons do not go on to strike another U-235 atom. These excess neutrons are said to be 'lost'. In a nuclear reaction, a chain reaction is kept under control by absorbing excess neutrons with 'control rods' of substances such as cadmium.

CHALLENGE 6.2A

Explosive energy

If you held a 10 kg lump of U-238 in your hand, it would feel slightly warm. But if you found two separate 10 kg lumps of U-238 and brought them together, you'd be blown apart and a crater 50 m deep would form. Is the source of the explosive energy the extra energy from your muscles in bringing the lumps together?

Einstein's mass–energy equivalence relationship

In 1905, long before the discovery of nuclear reactions, Albert Einstein (1879–1955), a German scientist who moved to the United States in 1933, published his now-famous special theory of relativity. This theory (discussed later in Unit 4) proposed that mass and energy are not separate quantities – rather, they are different forms of one another. The equation relating the two is:

$$\Delta E = \Delta m c^2$$

where ΔE = energy released or absorbed (J), Δm = change in mass or **mass defect** (kg) in a reaction, c = speed of light (3×10^8 m s^{-1}).

mass defect the difference between the mass of a nucleus and the sum of the component parts (symbol: Δm)

WORKED EXAMPLE 6.2A

If 1.0 g (1.0×10^{-3} kg) of a substance is converted completely into energy, how much energy is produced (in joules)?

SOLUTION

$\Delta E = \Delta m c^2$

$\Delta E = 1.0 \times 10^{-3}$ kg $\times (3 \times 10^8)^2$

$= 9 \times 10^{13}$ J

Calculating energy using mass defect

To find the energy change for a nuclear reaction, you must know the masses of each species in the equation for the reaction. The energy can be expressed as per atom of reactant or per kilogram of reactant.

Per atom of reactant

To calculate the energy change for a nuclear reaction in joules **per atom of reactant**:

- Calculate the sum of the masses of all the products (m_p) and the sum of the masses of all the reactants (m_r).
- Calculate the change in mass (Δm) by subtracting the combined mass of the reactants from the combined mass of the products ($m_p - m_r$).
- Convert the change in mass (the mass defect, Δm) into kg (1 u = 1.66×10^{-27} kg).
- Convert the change in mass (Δm, in kg) into its equivalent change in energy (in joule, J) using Einstein's equation ($\Delta E = \Delta m c^2$), where Δm is the mass defect in kg, and c is the speed of light (3×10^8 m s^{-1}). This gives the energy in J/atom of reactant. We can also call it joules per fission (J/fission).

Per kilogram of reactant

To calculate the energy change for a nuclear reaction in joules **per kilogram of reactant**:

- Calculate the mass of one atom of reactant in kg (= mass number in $\frac{\text{u} \times 1.66 \times 10^{-27}\ \text{kg}}{\text{u}}$)
- Calculate the number of atoms of reactant present in 1 kg of reactant (= $\frac{1.0\ \text{kg}}{\text{mass of one atom in kg}}$).
- Calculate the total energy produced for 1 kg of reactant: E_{total} = energy from one atom × number of atoms.

WORKED EXAMPLE 6.2B

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{94}_{38}Sr + ^{139}_{54}Xe + 3^{1}_{0}n + \text{energy}$$

For the U-235 fission reaction shown, calculate the energy released:

a in joules per fission of an atom of U-235 reacted

b in joules per kilogram of U-235 reacted.

SOLUTION

(See Appendix 1 for masses.)

a Joules per fission:

- Calculate the sum of the masses of all the reactants (m_r) and the sum of the masses of all the products (m_p).

Mass of reactants, m_r:

U-235	235.043 930 u
Neutron	+ 1.008 665 u
Total m_r	= 236.052 595 u

Mass of products, m_p:

Sr-94	93.915356 u
Xe-139	+ 138.918792 u
3 neutrons	+ (3 × 1.008 665) u

Total m_p = 235.860 143 u

- Calculate the change in mass (Δm) by subtracting the combined mass of the reactants from the combined mass of the products ($m_p - m_r$).

Mass defect, $\Delta m = |m_p - m_r|$ = |235.860 143 u – 236.052 595| u = 0.192 452 u

- Convert the change in mass (the mass defect, Δm) into kg (1 u = 1.66 × 10^{-27} kg).

Mass defect = 0.192 452 u × 1.6606 × 10^{-27} kg/u = 3.196 × 10^{-28} kg

- Convert the change in mass (Δm in kg) into its equivalent change in energy.

$\Delta E = \Delta m c^2$

= 3.196 × 10^{-28} × (3 × 10^8)^2 J

= 2.88 × 10^{-11} J (for one atom of U-235)

b Joules per kilogram:

- Calculate the mass of one atom of reactant in kg (= mass number in u × 1.66 × 10^{-27} kg/u).

Mass of one U-235 atom = 235.043 u × 1.66 × 10^{-27} kg/u = 3.90 × 10^{25} kg

- Calculate how many atoms of reactant are present in 1 kg of reactant.

Number of atoms of U-235 in 1 kg U-235 = $\frac{1 \text{ kg}}{3.90 \times 10^{-25} \text{ kg}}$ = 2.56 × 10^{24} atoms

- Calculate total energy produced for 1 kg of reactant.

Energy released by 2.56 × 10^{24} atoms = $\frac{2.88 \times 10^{-11} \text{ J}}{\text{atom}}$ × 2.56 × 10^{24} atoms

= $\frac{7.38 \times 10^{13} \text{ J}}{\text{kg}}$

Answer: 7.38 × 10^{13} J per kg (or J kg^{-1})

CHALLENGE 6.2B

TNT

Worked example 6.2A shows that when 1 g of a substance is converted completely to energy, 9×10^{13} J is released. By comparison, when 1 g of the explosive TNT is reacted, 4000 J of chemical energy released. When 1 g of petrol is burnt, 30 000 J of energy is released.

Comment critically on the flaw in this statement: ‘1 kg of uranium fuel releases 9×10^{16} J’.

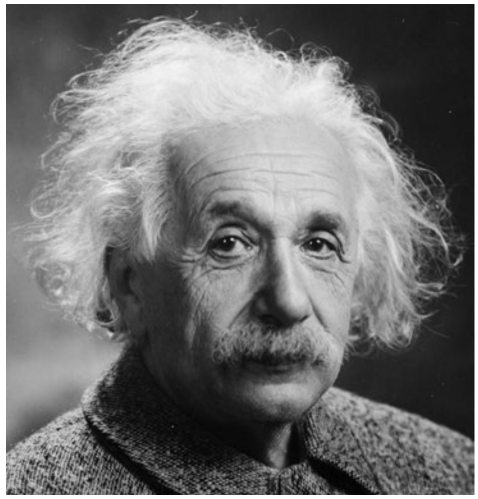

FIGURE 5 Einstein’s equation is used to convert change in mass into the equivalent change in energy.

CHECK YOUR LEARNING 6.2

Describe and explain

1. **Explain** why we still use models in nuclear physics.
2. **Explain** a neutron-induced nuclear fission reaction.
3. **Define** the term, ‘chain reactions’.
4. **Describe** the ‘liquid drop model’ of a nucleus undergoing fission.

Apply, analyse and interpret

5. **Structure** balanced equations for these neutron-induced fission reactions:
   - **a** $^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{84}_{36}Kr + ?^{1}_{0}n$
   - **b** $^{235}_{92}U + ^{1}_{0}n \rightarrow ^{137}_{52}Te + ^{?}_{?}? + 2^{1}_{0}n$
   - **c** $^{235}_{92}U + ^{1}_{0}n \rightarrow ^{152}_{60}Nd + ^{81}_{?}? + ?^{1}_{0}n$
6. Plutonium-239 is a nuclide that undergoes neutron-induced fission. A typical reaction is:

   $^{239}_{94}Pu + ^{1}_{0}n \rightarrow ^{133}_{55}Cs + ^{104}_{46}Pd + 3^{1}_{0}n$

   The exact masses of the nuclides are:

   m (Pu-239) = 239.052162 u

   m (Cs-133) = 132.905 452 u

   m (Pd-104) = 103.904 030

   m (neutron) = 1.008 665 u

   Determine the energy released for the reaction in:
   - **a** joules per atom of Pu-239
   - **b** joules per kg of Pu-239.
7. **Determine** how many joules would be released if 1 u of mass was completely converted to energy, given that 1 u of mass = 1.66×10^{-27} kg. Use $\Delta E = \Delta mc^2$.
8. **Determine** which of these neutron-induced reactions produces the greater amount of energy per fission:

   $n + ^{3}He \rightarrow ^{4}He + \gamma$ or $n + ^{1}H \rightarrow ^{2}H + \gamma$

   Use Appendix 1 for exact masses of nuclides. You can ignore the gamma rays, as they have no mass.
9. **Consider** the following fission reaction:

   $^{235}_{92}U + ^{1}_{0}n \rightarrow ^{90}_{38}Sr + ^{135}_{54}Xe + 11\,^{1}_{0}n + \text{energy}.$

   Determine the energy released in:
   - **a** J per fission
   - **b** J per kg of U-235.

   Note: Use Appendix 1 for exact masses of nuclides.

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- » **Student book questions** Check your learning 6.2
- » **Challenge** 6.2A Explosive energy
- » **Challenge** 6.2B TNT
- » **Increase your knowledge** Science as a Human Endeavour: using fission as a source of power

6.3 Nuclear fusion

KEY IDEAS

In this section, you will learn about:

+ nuclear fusion as a reaction.

The alpha bombardment of nitrogen carried out by Rutherford in 1919 can be classed as a fusion reaction:

$$^{4}_{2}\text{He} + ^{14}_{7}\text{N} \rightarrow ^{17}_{8}\text{O} + ^{1}_{1}\text{p}$$

Nuclear fusion is also occurring in the upper atmosphere, and forms the basis of C-14 dating:

$$^{14}_{7}\text{N} + ^{1}_{0}\text{n} \rightarrow ^{14}_{6}\text{C} + ^{1}_{1}\text{H}$$

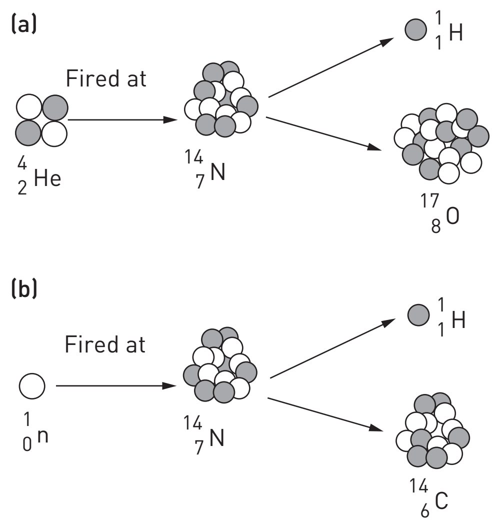


FIGURE 1 (a) Rutherford's alpha bombardment; (b) the upper atmosphere fusion of nitrogen

Scientists have been dreaming of producing a sustainable and controlled nuclear fusion on Earth for over 50 years. Trying to get nuclear fusion working in a controlled fashion is a difficult task. For two small nuclei to fuse, their massive electrostatic repulsions must be overcome. It normally takes more energy to do this than could ever be released, so very careful selection of nuclei is needed.

The first release of energy from a fusion reaction was in 1932 when John Cockcroft and Ernest Walton demonstrated the following reaction:

$$^{2}_{1}\text{H} + ^{3}_{1}\text{H} \rightarrow ^{4}_{2}\text{He} + ^{1}_{0}\text{n} + \gamma\,(2.8 \times 10^{-18}\text{ J, or 17.6 MeV})$$

The energy comes from the high binding energy per nucleon of the very stable helium nucleus compared with the smaller binding energy per nucleon of deuterium $^{2}_{1}\text{H}$ and tritium $^{3}_{1}\text{H}$.

Other fusion reactions that form helium nuclei include:

$$^{2}_{1}\text{H} + ^{2}_{1}\text{H} \rightarrow ^{3}_{2}\text{He} + ^{1}_{0}\text{n} + \gamma\,(1.7 \times 10^{-18}\text{ J, or 3.3 MeV})$$

$$^{2}_{1}\text{H} + ^{2}_{1}\text{H} \rightarrow ^{3}_{2}\text{He} + ^{1}_{0}\text{n} + \gamma\,(1.7 \times 10^{-18}\text{ J, or 3.3 MeV})$$

$$^{2}_{1}\text{H} + ^{3}_{2}\text{He} \rightarrow ^{4}_{2}\text{He} + ^{1}_{1}\text{H} + \gamma\,(2.928 \times 10^{-17}\text{ J, or 18.35 MeV})$$

The energy is normally given off in the form of gamma rays.

WORKED EXAMPLE 6.3

Consider the following fusion reaction:

$$^{2}_{1}H + ^{3}_{2}He \rightarrow ^{4}_{2}He + ^{1}_{1}H + \gamma$$

a Show that the energy released is 18.35 MeV.

b Express this as J per atom of $^{2}_{1}H$

c Express this as J per kilogram of $^{2}_{1}H$.

SOLUTION

a We can use atomic masses of the nuclides:

$m_r = 2.014102 + 3.016029 = 5.030131$ u

$m_p = 4.002603 + 1.007825 = 5.010428$ u

$\Delta = m_p - m_r = 5.010428 - 5.030131 = -0.019703$ u (the negative means energy is released)

$$\text{Energy (MeV)} = \Delta m \times \frac{931.5 \text{ MeV}}{u} = 0.019703 \times 931.5 = 18.3523 \text{ MeV} = 18.35 \text{ MeV}$$

b Energy (J) $= mc^2$

$= (0.019703 \text{ u} \times 1.66 \times 10^{-27}) \times (3 \times 10^8)^2$

$= 3.270698 \times (3 \times 10^8)^2 = 2.9436 \times 10^{-12}$ J $= 2.944 \times 10^{-12}$ J

c Energy per kg

Mass of 1 atom of H-1 $= 2.014102 \times 1.66 \times 10^{-27} = 3.3434 \times 10^{-27}$ kg

$$\text{Number of atoms of H-1 in 1 kg} = \frac{1 \text{ kg}}{3.3434 \times 10^{-27} \text{ kg}} = 2.9909 \times 10^{26} \text{ atoms}$$

$$\frac{\text{Energy}}{\text{kg}} = 2.9909 \times 10^{26} \text{ atoms} \times \frac{2.9436 \times 10^{-12} \text{ J}}{\text{atom}} = 8.80418 \times 10^{14} \text{ J} = 8.804 \times 10^{14} \text{ J}$$

Comparison of energy output between fission and fusion reactions

In Worked Example 6.2B it was shown that when U-235 undergoes a neutron-induced fission reaction, the energy output is 2.88×10^{-11} J per fission event, or 7.38×10^{13} J per kilogram of U-235.

The energy produced by a fusion reaction such as $4\,^{1}_{1}H \rightarrow ^{4}_{2}He + 2\,^{0}_{+1}e + \gamma$ can also be determined. Note: when we are doing mass defect calculations involving the production of beta particles, we ignore the mass of these particles as we lose two orbiting electrons from the hydrogen atoms at the same time. This always applies to any sort of beta decay reaction.

$m_r = 4 \times 1.007825 = 4.031300$ u

$m_p = 4.002603$ u (ignoring the β particles)

$\Delta m = m_p - m_r = 4.002603 - 4.031300$

$= -0.028697$ u (a negative value means energy is produced)

$$\Delta m \text{ (kg)} = 0.028697 \text{ u} \times \frac{1.66 \times 10^{-27} \text{ kg}}{\text{u}} = 4.765 \times 10^{-29} \text{ kg}$$

$$\Delta E = \Delta m c^2 = 4.765 \times 10^{-29} \times (3 \times 10^8)^2$$

$= 4.288 \times 10^{-12}$ J (per fusion event, that is, of $4\,^{1}_{1}H$ nuclei reacting).

To calculate energy per kilogram of $4\,^{1}_{1}H$ we need to know the mass of $4\,^{1}_{1}H$.

We know it is 4 u of mass, which is:

$$4 \text{ u} \times \frac{1.66 \times 10^{-27} \text{ kg}}{\text{u}} = 6.64 \times 10^{-27} \text{ kg}$$

Therefore, to obtain the energy per kg we divide the energy of 4.288×10^{-12} J by 6.64×10^{-27} kg, which equals $6.46 \times \frac{10^{14} \text{ J}}{\text{kg}}$.

TABLE 1 Comparison of fission and fusion reactions

	Fission of U-235	Fusion of $4\,^1_1H$	Comparison
J per event	28.8×10^{-12} J	4.29×10^{-12} J	fission = 7 × fusion
J per kg	$7.38 \times 10^{13} \frac{J}{kg}$	$6.46 \times 10^{14} \frac{J}{kg}$	fusion = 8 × fission

Study tip

Further information about controlled and uncontrolled fusion can be found on your obook assess.

In the comparison of reactions in Table 1, note that fission puts out 7 times as much energy per event as fusion. However, because the fission nucleus is so big and heavy, the 'per kg' value is much lower at $\frac{1}{8}$ of the fusion output. We can say that fusion produces more energy per unit of mass as the fusion nuclei are so small.

Controlled fusion

controlled fusion a self-sustaining thermonuclear fusion reaction for the production of electricity

Since the 1950s, the use of **controlled fusion** for electricity production has been promoted as technically feasible. The International Thermonuclear Experimental Reactor (ITER) is an international nuclear fusion research and engineering megaproject. It is an experimental nuclear fusion reactor being built in southern France and the project will be the world's largest magnetic confinement plasma physics experiment.

The ITER fusion reactor has been designed to produce 500 megawatts of output power for around 20 minutes while needing 50 megawatts to operate. The reactor aims to demonstrate the principle of producing more energy from the fusion process than is used to initiate it – something that has not yet been achieved in any fusion reactor.

ITER's expected cost has gone from \$5 billion to \$20 billion since first proposed, and the scheduled date for full-power operation is now 2027.

Uncontrolled fusion

uncontrolled fusion a nuclear reaction in which the resulting energy is released in an uncontrolled manner, as it is in thermonuclear weapons ('hydrogen bombs') and in most stars

hydrogen bomb a thermonuclear weapon that employs the fusion of isotopes of hydrogen

While nuclear fusion for peaceful purposes (such as electricity production) seems a long way off, nuclear fusion in the form of **uncontrolled fusion** has already been harnessed for destructive purposes in the form of the **hydrogen bomb**. This type of bomb is technically more advanced than the fission bomb and potentially more devastating.

Hydrogen bomb (H-bomb)

After the United States dropped a fission bomb on Japan towards the end of the war in 1945, the Soviet Union decided to develop its own fission bomb in the late 1940s. Not be outdone, the United States began to work on new technology known as the thermonuclear or hydrogen bomb (H-bomb). H-bombs differ from fission bombs in that most of their explosive power comes from nuclear fusion. The first successful fusion bomb detonation was in 1952 in the United States. It was said the explosion was 'brighter than a thousand suns' (Figure 2).

The explosive power of a fusion bomb is thousands of times greater than that of fission devices.

How a fusion bomb works

A fusion bomb consists of a strong metal case packed with chemical and nuclear fuel. When the chemical explosive is fired, the U-235 core is compressed to a smaller sphere. This causes it to undergo fission.

FIGURE 2 The first fusion bomb (known as 'Mike') was detonated on 31 October 1952.

The high energy and temperature initiate a fusion reaction between the deuterium and tritium inside it:

$$ {}^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} + \gamma \text{ and } {}^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{1}\mathrm{H} + \gamma $$

All these events happen in about 600 billionths of a second, resulting in an immense explosion about 700 times more powerful than the fission explosion at Hiroshima.

CHALLENGE 6.3

Poetry

Poet W. H. Auden wrote in his poem *Marginalia*:

No tyrant ever fears
His geologists or his engineers.

What do you suspect Auden meant by this? What evidence would he need to substantiate this claim?

CHECK YOUR LEARNING 6.3

Describe and explain

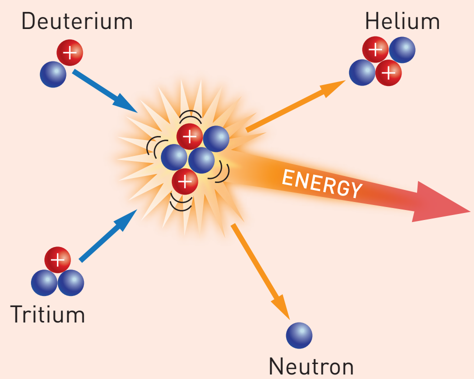
1 **Describe** nuclear fusion.

Apply, analyse and interpret

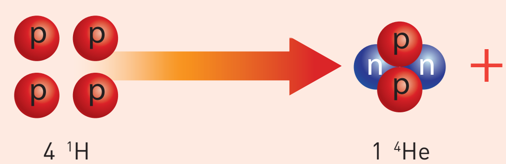
2 **Compare** fission and fusion by arguing what is better about fission than fusion, and in what way fusion is better than fission.

3 **Deduce** a balanced equation for these fusion reactions.

a



b



c $ {}^{3}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} \rightarrow {}^{4}_{2}\mathrm{He} + ? $

Investigate, evaluate and communicate

4 An Australian $1 coin has a mass of 9.0 grams. Using the formula $E = mc^2$, the mass is equivalent to 8.1×10^{14} J. This is about the total energy consumption of a town of 40 000 people for 1 year (at 5817 kWh per person per year). **Evaluate** how this can be.

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  Science as a Human Endeavour: Nuclear fusion in stars

CHAPTER 6

Review

Summary

6.1
- Artificial transmutation is the process in which an isotope is intentionally caused to change by nuclear processes into an isotope of another element (distinct from natural radioactivity) e.g. neutron bombardment of U-235.

6.2
- Nuclear fission is a nuclear reaction in which a large unstable nucleus splits, forming two (or more) smaller, more stable nuclei and releasing neutrons and energy.
- Nuclear fusion is a nuclear reaction in which two or more atomic nuclei combine to form one or more different, heavier atomic nuclei and subatomic particles.

6.3
- Mass and energy are not separate quantities – they are different forms of one another. The equation relating the two is $\Delta E = \Delta mc^2$.

Key terms

- artificial transmutation
- chain reaction
- deuterons
- mass defect
- nuclear fission
- nuclear fusion
- nuclear reactions

Key formulas

Mass-energy equivalence relationship	$\Delta E = \Delta mc^2$

Revision questions

The relative difficulty of these questions is indicated by the number of stars beside each question number: ★ = low; ★★ = medium; ★★★ = high.

Multiple choice

1 Uranium-235 releases energy in a process called fission. Fission is:

- **A** the addition of a neutron to the nucleus.
- **B** the release of gamma radiation.
- **C** the combination of two smaller nuclei to form a larger one.
- **D** the splitting of the nucleus into two smaller nuclei.

2 The following fusion reaction occurs in the Sun is:

$^{4}_{2}He + ^{3}_{2}He \rightarrow ^{7}_{4}Be$

The masses of the nuclei including electrons are ^{3}He = 3.016 029 u, ^{4}He = 4.002 603 u, ^{7}Be = 7.016 929 u. Use your table of nuclides (Appendix 1) to determine whether the energy of the reaction is closest to:

- **A** 920 MeV absorbed.
- **B** 1.6 MeV absorbed.
- **C** 920 MeV released.
- **D** 1.6 MeV released.

3 Determine which of the following statements is incorrect.

- **A** Mass number is the sum of all protons and electrons in an atom.
- **B** Mass defect is the difference in mass between a nucleus and its component particles.
- **C** Nuclei with highest binding energies are the most stable nuclei.
- **D** Einstein postulated the theory of relativity in which he stated that mass and energy are equivalent.

4 When ^{235}U is bombarded with one neutron, fission occurs and the products are three neutrons, ^{94}Kr and which one of the following?

- **A** ^{139}Ba
- **B** ^{141}Ba
- **C** ^{139}Ce
- **D** ^{139}Xe

5 Determine which of the following isotopes has the highest nuclear binding energy per nucleon. (No calculation is necessary.)

- **A** ^{4}He
- **B** ^{16}O
- **C** ^{32}S
- **D** ^{55}Mn

Short answer

Describe and explain

★ **6** **Define** artificial transmutation, nuclear fission and nuclear fusion.

★ **7** **Explain** what it means to have a fission chain reaction.

★ **8** State Einstein's mass–energy equivalence relationship in symbol form and **explain** its meaning.

★ **9** **Calculate** the energy released (in MeV and J) per nucleon in the neutron-induced fission reaction of:

n + U-235 → Kr-92 + Ba-142 + 2n

Note: *m*(Ba-142) = 141.916432 u;
m(Kr-92) = 91.926173 u

Apply, analyse and interpret

★ **10** **Distinguish** between artificial transmutations and natural radioactive decay.

★ **11** **Identify** the names of these bombarding particles: $^{1}_{1}p$, $^{2}_{1}H$.

★ **12** **Distinguish** between natural radioactive decay and artificial transmutation.

★ **13** **Determine** which nuclide has the highest binding energy per nucleon by using the graph of variation in binding energy per nucleon.

★ **14** **Determine** the products of this proton bombardment reaction: $^{9}_{4}Be + ^{1}_{1}H \rightarrow ^{2}_{1}H + ?$

★★ **15** **Consider** the following neutron-induced fission reaction:

$n + ^{238}_{92}U \rightarrow ^{96}_{38}Sr + ^{140}_{54}Xe + 3^{1}_{0}n$

Given *m*(Sr-96) = 95.921707 u and *m*(Xe-140) = 139.921646 u, calculate the energy released in MeV and J.

★★ **16** **Consider** the following fission reaction:

$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{55}Cs + ^{93}_{37}Rb + 2^{1}_{0}n$

Calculate the energy released in:

a MeV **b** joules

★★ **17** **Consider** the following reaction:

$4\,{}^{1}_{1}H \rightarrow {}^{4}_{2}He + 2\,{}^{0}_{+1}e$

Calculate the energy released when:

a 4 ${}^{1}_{1}H$ nuclei fuse

b 1 kg of ${}^{1}_{1}H$ fuses.

★★★ **18** **Determine** the following for these two nuclear reactions:

i ${}^{239}_{94}Pu + {}^{1}_{0}n \rightarrow {}^{137}_{52}Te + {}^{100}_{42}Mo + 3\,{}^{1}_{0}n$

ii $2\,{}^{2}_{1}H \rightarrow {}^{4}_{2}He$

a Which of the reactions produces the most energy per kilogram of reactant?

b **Evaluate** the conclusion about these reactions: 'Fusion produces more energy per kilogram than a fission reaction'.

Investigate, evaluate and communicate

★ **19** **Solve** by balancing these fission reactions:

a ${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{133}_{?}Sn + {}^{101}_{?}? + ?\,{}^{1}_{0}n$

b ${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{138}_{?}Xe + {}^{?}_{?}? + 3\,{}^{1}_{0}n$

★★★ **20** In a particular fission event of U-235 by slow neutrons, no neutrons are emitted. **Decide** the answers to the following:

a If one of the fission fragments is Ge-83, what is the other one?

b What is the mass in kilograms of each fragment ($1\ u = 1.6606 \times 10^{-27}$ kg)?

c If the total energy released per fission event is 170 MeV, and half goes to each nuclide, how much does each nuclide get (in MeV)?

d How much energy does each nuclide get in joules ($1\ MeV = 1.6 \times 10^{-13}$ J)?

e If this energy is converted to kinetic energy for each fragment, what are their initial speeds $\left(KE = \frac{1}{2}mv^2\right)$?

★★★ **21** Nuclear fission of U-235 releases about 3.5×10^{-11} J of energy per fission event.

a **Calculate** this energy as J per kg of U-235 reacted.

b **Determine** how many times greater this is than the combustion of methane, which releases 50 MJ per kg.

★★★ **22** Earth receives 1.8×10^{14} kJ per second of solar energy.

a **Determine** what mass of solar material is converted to energy over a 24-hour period to provide the daily amount of solar energy to Earth.

b If coal releases 32 MJ of energy per kilogram, **determine** what mass of coal must be burnt to provide this same amount of energy.

★★★ **23** A nuclear fission reaction written as U-235 (n, 2n) Cs-138, Rb-96 implies that U-235 is struck by a neutron to produce two neutrons and the two isotopes as shown. **Prove** that the energy output for that reaction is 177 MeV.

★★★ **24** The 'Little Boy' fission bomb dropped on Hiroshima, Japan, to end WWII contained 64 kg of enriched uranium. When the bomb exploded only 0.88 kg of the U-235 underwent fission. Each U-235 atom split into two radionuclides. One of the long-term effects from a nuclear explosion is the radioactive fallout.

a **Determine** how many radioactive nuclei would each human would have breathed in if all radioactive fission products were spread evenly among the human population at the time (2.4 billion).

b **Propose** why this is not a realistic calculation. Hint: calculate how many atoms of U-235 are in 0.88 kg and double that to get the number of radionuclides.

★★★ **25** Two naturally occurring radioactive decay reactions are responsible for much of the Earth's internal heating: the alpha decay of uranium-238: ${}^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$, and the alpha decay of thorium-232: ${}^{232}_{90}Th \rightarrow {}^{228}_{88}Ra + {}^{4}_{2}He$. **Propose** which of these two contributes the greater amount of heat energy per kilogram to the Earth.

FIGURE 1 The Earth is heated internally due to natural radioactive decay.

★★★ 26 **Determine** which one of the following fusion reactions releases the most energy per fusion event:

a $^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n$

b $^{2}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{2}He + ^{1}_{0}n$

c $^{2}_{1}H + ^{3}_{2}H \rightarrow ^{4}_{2}He + ^{1}_{1}p$

In equation (c), be careful to use the mass of the proton ($^{1}_{1}p$), not the mass of a hydrogen atom ($^{1}_{1}H$).

★★★ 27 The Sun produces 1.86×10^{38} neutrinos per second. This is called the solar neutrino flux at its surface.

a **Determine** how many of these fall on Earth's surface per second;

b **Deduce** how many of these fall on 1 cm^2 area of the Earth's surface per second. Note: radius of Sun's orbit to Earth = 149.6×10^9 m; diameter of Earth = 12742 km; surface area of a sphere = $4\pi r^2$.

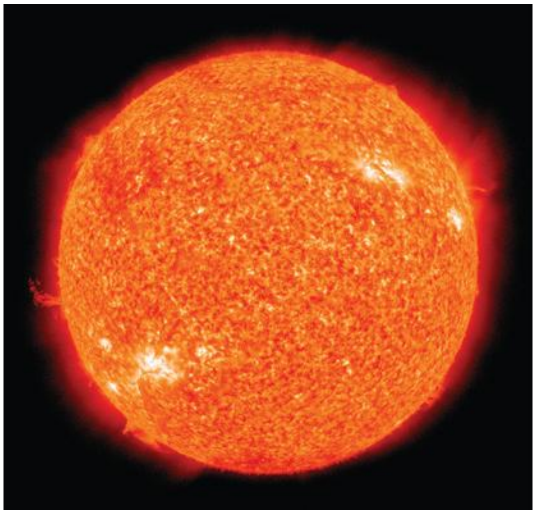

FIGURE 2 The Sun produces 1.86×10^{38} neutrinos per second

★★★ 28 In the carbon cycle that occurs on the Sun, He-4 is built from four protons and C-12. First, C-12 absorbs a proton to form a nucleus, X_1. Then X_1 decays by positron emission to X_2, which then absorbs a proton to become X_3, which itself absorbs a proton to become X_4. X_4 then decays to X_5 by positron decay and X_5 reacts via: $X_5 + \text{proton} \rightarrow X_6 + \alpha$.

a **Deduce** the formulas of X1 to X6 by writing out complete balanced nuclear equations.

b **Propose** a balanced net reaction by summing the six reactions and write a balanced net equation.

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CHAPTER 7

Current, potential difference and energy flow

When you run a comb through your hair you may hear some crackles, or your hair may stand up and be attracted to the comb. You have produced an electric charge by friction in a process called 'electrification'. Electric charge is very important in nature. It is responsible for many natural effects such as lightning strikes. However, much of our modern technology relies on making and controlling electric charges. To do this, we need to understand the nature of electric charge, current, energy and voltage. By the end of this chapter you should be able to explain why a 6 V motorcycle battery can be more powerful than a 12 V car battery.

OBJECTIVES

- → Recall that electric charge can be positive or negative.
- → Recall that electric current is carried by discrete electric charge carriers.
- → Recall the law of conservation of electric charge.
- → Define electric current, electrical potential difference in a circuit, and power.
- → Solve problems involving electric current, electric charge and time.
- → Recall that the energy available to electric charges moving in an electrical circuit is measured using electrical potential difference.
- → Solve problems involving electrical potential difference.
- → Explain why electric charge separation produces an electrical potential difference (no calculations required to demonstrate this).
- → Solve problems involving power.

Source: *Physics 2019 v1.2 General Senior Syllabus Queensland Curriculum & Assessment Authority*

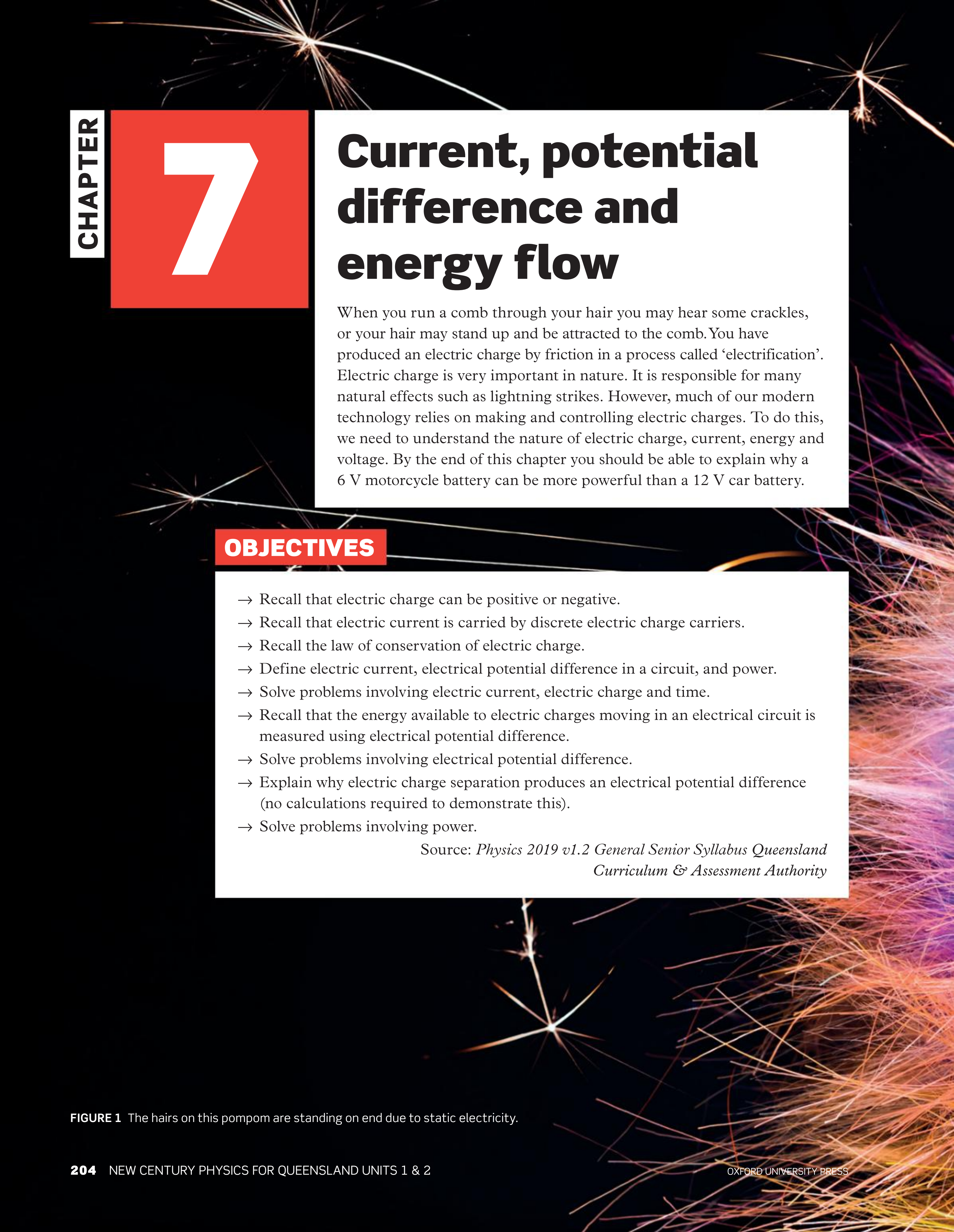

FIGURE 1 The hairs on this pompom are standing on end due to static electricity.

MAKES YOU WONDER

In this chapter we will be examining some aspects of electric circuits that will help to answer questions such as:

→ After rubbing your head on a balloon, will your hair stay standing up or will it go back down?
→ When you bounce on a trampoline, why are you sometimes zapped by electricity when you get off it?
→ Why do you sometimes hear snaps and crackles when you comb your hair? Is the same thing happening when you take off a synthetic shirt and experience a similar feeling?
→ At the bowsers at petrol stations, why are there signs that state ‘Turn off your phone’?
→ Rubbing a plastic pen on your sleeve can give it a voltage of 10 000 V. Why doesn’t this kill you?

These observations are just some ‘phenomena’ associated with electric charge. Phenomena are events that can be observed through the senses or can be scientifically described or explained.

7.1 Charge

KEY IDEAS

In this section, you will learn about:

- the classification of charge as positive and negative
- conductors and insulators.

charge
one of the basic properties of the elementary particles (electrons and protons) which can be positive or negative, and occurs in whole number (discrete) units

You may wonder, 'Who gave the electron a negative **charge**?' For years you've learnt that electrons have a negative charge and protons have a positive charge. But this is just a convention, made up by humans. The Greeks knew that taking pieces of amber (tree resin) and rubbing it with animal fur would cause feathers, hair and straw dust to stick to the amber. In 1733, French investigator Charles du Fay discovered two types of charge. He called them vitreous (glass rubbed by silk) and resinous (amber rubbed by fur), and noted that these two previously unnamed types of charge cancelled each other out.

The charges were given a name in 1747 by US scientist Benjamin Franklin. He found that rubbing glass created a charge, and if you put your hand on the glass you acquired (received) the same charge. He said that person then had an excess of charge – that charge was added to them. Franklin said that as adding was positive (as in mathematics), the charge on the glass when rubbed with silk was positive (+). When the positively charged person touched the ground, the charge went away. Franklin said the ground must have an opposite charge that he called minus (–), which we now call negative.

Charge is classified as being either positive (+) or negative (–). By 'classify' we mean arranged into categories according to shared characteristics.

When the electron was discovered by J. J. Thomson in 1897, it was shown to have the same charge as a plastic rod rubbed with fur, negative. The word 'electric' comes from the Greek word for amber, *electron*. So, electrons were considered to be particles with negative charge. When electrons are removed from an object such as glass, the glass is left with an excess of positive charges. We have since found that protons are positively charged.

The charge carriers

You have learnt that atoms are the building blocks of all matter. An atom consists of a very small and dense central nucleus, which contains protons and neutrons, and layer-like regions called clouds surrounding this nucleus, which contain electrons.

Figure 1 shows the relative diameters of a typical atomic nucleus as well as the outer electron cloud for a general atom. From this type of model, it is possible to conclude that the atom is mostly empty space. Ernest Rutherford came to this same conclusion around 1913 using alpha particle scattering experiments.

The particles in the nucleus are very tightly bound together, with the protons being positively charged and the neutrons being neutral (no net charge). The electrons, especially the outermost ones, are discrete (individual) particles and are very loosely bound to the nucleus in most atoms. 'Discrete' means individually separate and distinct. Hence, discrete charge carriers are individual particles such as electrons, protons and ions.

Any atom that has equal numbers of protons and electrons is said to be neutral as it has no net electric charge. Neutrons simply act as a nuclear glue and do not alter the positive–negative balance of the atom. The hydrogen atom is the simplest atom in nature. It only has

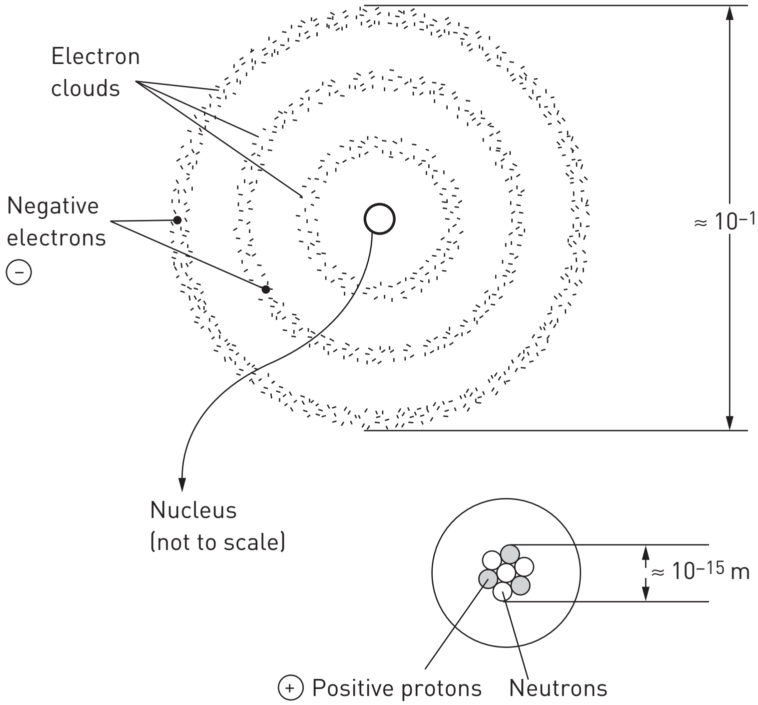

FIGURE 1 Simplified diagram showing the size of the atom and its constituents

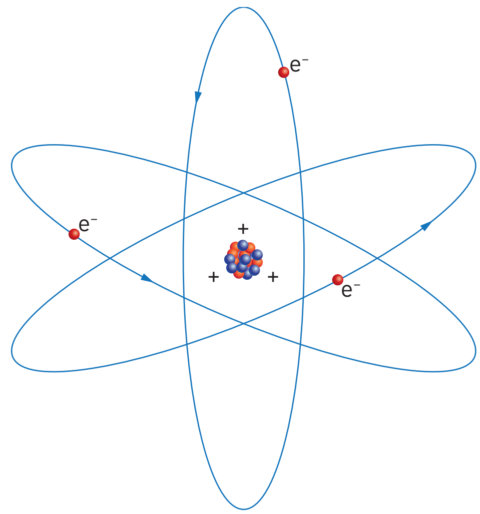

FIGURE 2 A simplified 'planetary' model of an atom showing the positive central nucleus and orbiting electrons. The electron doesn't really travel around in orbits like planets around the Sun, but the model helps explain the location of the two types of charge. Note that there are three positive charges in the nucleus, and this is balanced by three negative charges in the electron cloud.

TABLE 1 The properties of the three fundamental atomic particles

	Electron	Proton	Neutron
Relative charge	–1	+1	0
Coulomb charge	-1.6×10^{-19}	$+1.6 \times 10^{-19}$	0
Mass	9.11×10^{-31} kg	1.673×10^{-27} kg	1.675×10^{-27} kg
Atomic location	orbital cloud	central nucleus	central nucleus
Discovered	1897 by J. J. Thompson	1913 by E. Rutherford	1932 by J. Chadwick

1 electron and 1 proton, whereas lawrencium (Lw), a very complex atom, has 103 electrons, 103 protons and 157 neutrons. If an individual atom of any element is made to gain or lose some of its electrons, it is said to have become an **ion** (coined in 1834 by Michael Faraday; Greek *ienai* means 'to go', because they move around).

ion
an atom that has lost or gained electrons

Positive ions have lost electrons and negative ions have gained electrons over and above the normal atomic number. Ions are important in various types of chemical reactions. You would have used tables of common ions in your earlier science work.

A lithium atom ($^{7}_{3}Li$) has 3 protons ($3p^+$) and 3 electrons ($3e^-$) and is electrically neutral. If one of the electrons is stripped away, the atom would still have 3 protons (+3) but only 2 electrons (–2). Its net charge would be the sum of +3 and –2, which is +1. It would have the formula Li^{1+} (or just Li^+). Likewise, a fluorine atom $^{19}_{7}F$ has 7 protons and 7 electrons ($7p^+$ and $7e^-$) and is electrically neutral. If it gains an electron, it will become an F^- ion.

Measurement of charge

coulomb
a measure of electric charge. One coulomb (C) is the charge on 6.24×10^{18} elementary charges

Electric charge is measured in units called **coulombs** (symbol C). The unit is named after French physicist Charles-Augustin de Coulomb (1736–1806). One coulomb of electric charge is equivalent to the charge on 6.24×10^{18} electrons. If an electrified object has an excess of

elementary charge the magnitude of the electric charge carried by a single electron or single proton

6.24×10^{18} electrons or has lost this number of electrons, it will have a charge of one coulomb (1 C) negative or positive respectively. An **elementary charge** (q_e) is the magnitude of the electric charge carried by a single proton or a single electron. The charge on a single electron (q_e) can be calculated as $\frac{-1\ \text{C}}{6.24 \times 10^{18}} = -1.6 \times 10^{-19}$ C.

An electron has a charge of $-q_e$ and a proton has a charge of $+q_e$. Note that we can only speak of 'excess' charge as we don't know how many electrons and protons make up the object, just the number that are in excess one way or the other.

$$\text{Number of elementary charges} = \frac{\text{total charge}}{\text{elementary charge}}$$

$$n = \frac{Q}{q_e}$$

Study tip

The symbol Q is the SI unit symbol for the quantity of charge on an object, however it is fairly common to use a lowercase q as well. You can use either. The symbol q_e (note the subscript e) stands for 'elementary charge' and the value of q_e is 1.6×10^{-19} C.

WORKED EXAMPLE 7.1

Calculate the number (n) of excess electrons in a charge of 2.5 C.

SOLUTION

$n = \frac{Q}{q_e}$

$= \frac{2.5}{1.6 \times 10^{-19}}$

$= 1.5625 \times 10^{19}$ electrons

$= 1.6 \times 10^{19}$ electrons (2 sf)

Study tip

Information about producing a charge can be found on your obook assess.

Can we have fractional charge?

The charge on the electron q_e of 1.6×10^{-19} C is said to be the fundamental charge. It is also called the 'elementary' charge, hence the subscript 'e'. All charged objects in nature are integral multiples of this basic quantity of charge, meaning that all charges are made of combinations of a basic unit of charge. An electron has a charge of $-q_e$ and a proton has a charge of $+q_e$. However, you will see in Unit 4 that protons and neutrons are made up of more fundamental particles called 'quarks'. A 'down' quark can have a fractional charge of $-\frac{1}{3}q_e$ and an 'up' quark $+\frac{2}{3}q_e$.

Information about producing a charge can be found on your obook assess.

Conservation of charge

law of conservation of charge the net amount of charge produced in any transfer process is zero

Frictional charging involves a transfer of negative charge or electrons from one object to another. Objects can never gain or lose protons in this process – they stay in place. It is the electrons that move. When a single electron leaves a glass rod for the silk, the silk has an excess of one electron (–1) and the rod now has an excess of one proton (+1). The net amount of charge lost by one object of the pair is gained by the other. We can state a more general law called the **law of conservation of charge**:

In other words, the total charge before a transfer process equals the total charge after the process.

Imagine rubbing a glass rod with a piece of silk, both of which are neutral (see Figure 3). The diagram shows that 5 electrons have jumped from the glass to the silk, leaving the glass with a +5 charge, and the silk now has a –5 charge, which adds to zero. Charge is conserved, as the charge (before) of zero equals the charge (after) also of zero. The amount of charge produced (+5, –5) is zero, as the law states.

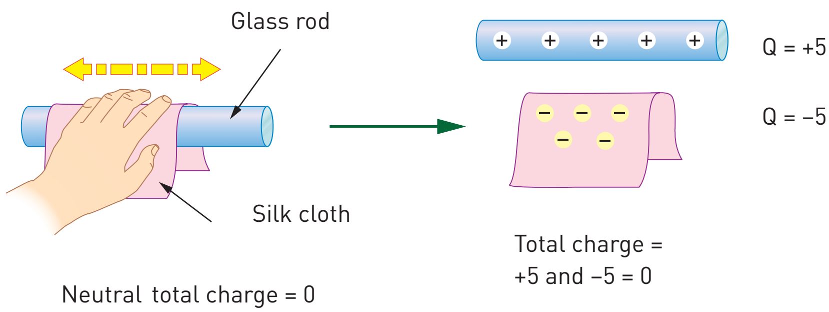

FIGURE 3 Loss of electrons by glass = gain of electrons by silk

conductor
a substance that allows free movement of charge through it

insulator
a substance that does not allow free movement of charge through it

Conductors and insulators

What is the difference in the way charge behaves in plastic and metal? Plastic and metal are both solids, but they behave differently with electric charge. In solids, the atoms are generally arranged in a simple geometric pattern or lattice. In liquids and gases, the atoms are much freer to move. A metallic solid has a regular lattice array of atomic nuclei and the outermost electrons of each atom are quite easily able to move throughout this lattice array (Figure 4). This type of arrangement is called metallic bonding. Metals are called good electrical **conductors** as any charge placed on them is free to move through the lattice. We say that the mobile charge carriers are the electrons.

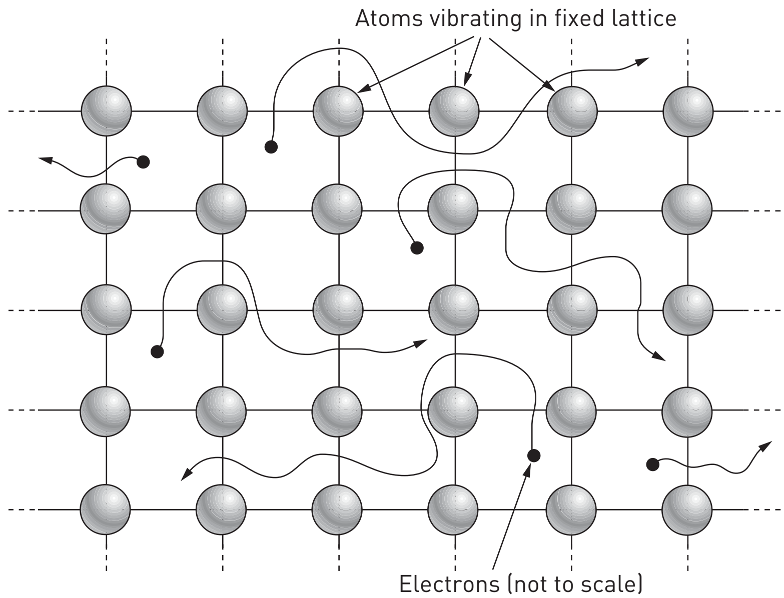

FIGURE 4 Lattice of fixed atoms and their mobile electrons

Other substances that do not allow free charge movement, or whose atomic electrons are not free to move, are called **insulators**. The most common insulators used to prevent the flow of electric charge are rubber, plastics, paper, glass and ceramics. Charges placed onto any conductor will be free to evenly distribute over the surface of the conductor, whereas charge placed onto the surface of any insulator will stay in the same place.

Study tip

Some examples of conductors and insulators can be found on your obook assess.

CHECK YOUR LEARNING 7.1

Describe and explain

1 **Explain** the concept of charge and how it can be classified.

2 **Describe** the difference between an insulator and a conductor.

3 **Calculate** the number of excess elementary particles in a charge of:

a +10.0 C   b 1.45 μC   c −15 pC.

4 **Calculate** the charge in coulombs of:

a 1.25×10^{25} electrons

b 6.02×10^{23} electrons.

5 Figure 5 shows the three quarks that make up a proton. **Demonstrate** that the sum of the charges adds up to the charge on the proton.

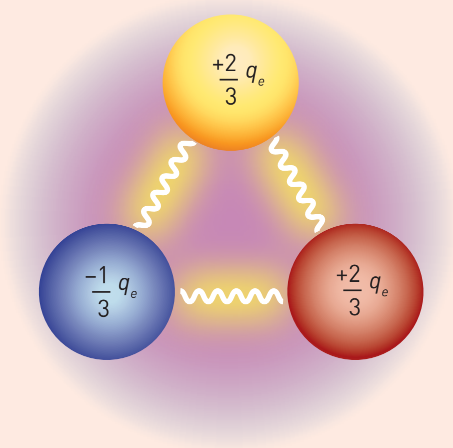

FIGURE 5 Quarks in a proton

6 **Explain** if you can have an object with a charge of 3×10^{-20} C.

7 A neutral helium atom is stripped of all its electrons. **Calculate** the overall charge on the resulting particle.

8 When a glass rod is rubbed with silk it becomes positive and the silk becomes negative, yet both attract dust. **Explain** whether dust has a third type of charge that is attracted to both positive and negative.

9 **Identify** one of the following as the correct reason why metals are good conductors.

A Metals contain free electrons.

B The atoms in metals vibrate more easily than in non-conductors.

C Metals have bigger gaps between their atoms than in insulators.

D The atoms in metals can move about.

Apply, analyse and interpret

10 **Categorise** the following materials into electrical conductors and electrical insulators: copper, PVC plastic, aluminium, silver, polythene, dry air, glass, carbon, salt solution, sugar solution.

11 A plastic rod is rubbed with fur and the rod acquires a +50 μC charge. **Determine** the charge on the fur.

12 Two objects with different initial quantities of charge are brought together and the charge redistributes, as shown by the final state in Table 2. **Determine** the charge on the second object in each of these three cases, using the law of conservation of charge.

TABLE 2

Initial state (μC)		Final state (μC)	
Object A	Object B	Object A	Object B
+10	−6	+4	?
+20	?	0	−20
+5	?	+2	−10

Investigate, evaluate and communicate

13 An atom of oxygen has 8 protons, 8 neutrons and 8 electrons. In a reaction, it gains electrons and finishes up with 10 electrons. **Predict** the final overall charge.

14 **Propose** why a car always attracts dust right after it is polished. (Note that car wax and car tyres are insulators.)

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» Increase your knowledge
Making charge with the Van der Graaf generator

» Increase your knowledge
Producing a charge
Examples of conductors and insulators

» Video
Charged rod and water trickle

7.2 Current and voltage

KEY IDEAS

In this section, you will learn about:

+ electric current.

voltage
a measure of electric potential energy per unit charge, measured in joules per coulomb; often referred to as electric potential

volts
a unit of electric potential or voltage, equivalent to 1 joule per coulomb of charge

Voltage and **volts** are terms you are probably familiar with. Your power supply at home is 240 volts, the battery in the car is 12 volts and the cell in a torch is 1.5 volts. So how did these power sources come about and what does the number of volts mean – is it energy or something else?

The electrical age began around 200 years ago when it was discovered how to store electrical charge, and thus control it rather than just deal with its electrostatic effects. Italian scientists Luigi Galvani (1737–1798) and Count Alessandro Volta (1745–1827) experimented with electrical effects in animal tissues, showing that the nervous system is electrically operated. Volta was able to produce the first example of an electric battery, which he called a 'pile', constructed from a series of pairs of zinc and copper electrodes separated by moist cloth layers. Today we call this apparatus a voltaic battery or just a battery.

Electric current

electric current
the rate of motion of electric charge carriers from one part of a conductor to another (symbol: *I*; SI unit: ampere; unit symbol: A)

When a battery is connected across a light bulb, charge flows through the wires. This is called the **electric current**, from a Latin word meaning 'to run'. It is a little like running – you can have big or small amounts of electric charge running and it can run at different speeds. The actual electric current in the wire is the total amount of charge Q (measured in coulombs) passing any given point in the wire every second over a time period, t.

$$I = \frac{Q}{t}$$

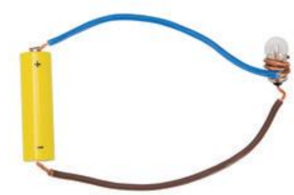

FIGURE 1 When a battery is connected to a light bulb, charge flows through the wires.

The symbol for current is I, and the unit of electric current is the ampere, with the symbol A. One ampere of electric current is thus a flow of charge of 1 coulomb per second. The term ampere is unofficially shortened to amp or amps.

1 A = 1 C per second = 6.25×10^{18} electrons per second

One ampere of current is quite large. Household appliances use typically up to about 20 A. For instance, a light uses about 0.25 A, a microwave oven 3 A, and a stove about 15 A. Inside electronic devices, currents of microamps (μA) or milliamps (mA) are more common. Electric current is measured with an ammeter.

TABLE 1 Units and symbols related to electric current

Physical quantity	Quantity symbol	Unit	Unit symbol
Electric charge	Q	coulomb	C
Current	I	ampere	A

WORKED EXAMPLE 7.2A

A charge of 30 C passes through a light bulb in 1 minute. What is the current in the bulb?

SOLUTION

$$I = \frac{Q}{t}$$
$$= \frac{30}{60}$$
$$= 0.5 \text{ A}$$

WORKED EXAMPLE 7.2B

A current of 2 A passes through a light bulb in a torch. Calculate how many:

a coulomb of charge passes in 1 second.

b electrons pass in 1 second.

SOLUTION

a $I = 2\text{A}, t = 1 \text{ s}, Q = ?$

$$I = \frac{Q}{t}$$

$Q = It = 2 \times 1 = 2$ coulomb (2 C)

b $$n = \frac{Q}{q_e}$$
$$= \frac{2}{1.6 \times 10^{-19}}$$
$$= 1.25 \times 10^{19} \text{ electrons}$$

You could also say that 1 C = 6.25×10^{18} electrons, so 2 C = $2 \times (6.25 \times 10^{18}) = 1.25 \times 10^{19}$ electrons.

conventional current
the motion of charge in the same direction as the positive charge flow; opposite to electron flow

What is conventional current?

Experiments were carried out with electricity and electrostatic charge long before the nature of electrons was discovered. In the 1730s, Benjamin Franklin used the term 'positive charge' in his early experimental work on electric current. He assumed that the charges in motion in conductors were positive charges and that they flowed along conductors from the positive terminal to the negative terminal (a little like water naturally flowing downhill). It is still common in physics and electric circuit analysis to refer to **conventional current** as the motion of positive charges from the positive terminal of a battery to the negative terminal. This is the convention used in this textbook and, although physically incorrect, is accepted as the international convention. This ensures clear communication of ideas and findings around the world.

Electron flow is the direction of electron motion in a conductor from negative to positive. One amp of conventional current in one direction is the same as one amp of electron flow in the opposite direction.

Note that in physics the term 'electric current' means conventional current unless specified.

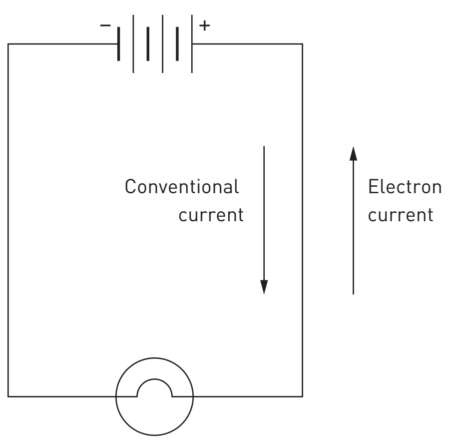

FIGURE 2 Conventional current is opposite to electron flow. We use the term 'current' to mean conventional current.

Direct current

When electric charge flows from the source of charge around a circuit in the one direction (as in Figure 3), the type of current is called direct current (DC). Batteries and voltaic cells provide DC. The magnitude and direction of the flow is constant over time.

When considering the flow of electric charge, a water model can be a useful analogy (Figure 3). The water pump is the equivalent of the electric battery. The water pipes are the equivalent of the electrical conductors, and the water itself is analogous to the electric charges in motion (the current). Note that as the water flows around the pipe circuit, it can provide energy to run a water wheel – just as charge flowing around an electric circuit can provide energy to operate a light bulb. In the water pipes, water never gets used up – it just keeps getting recycled. The same thing occurs with electric charge. The electric charge doesn't get used up – it just gives up its energy but keeps flowing until the battery energy is reduced to zero as a result of energy being transferred to the light bulb.

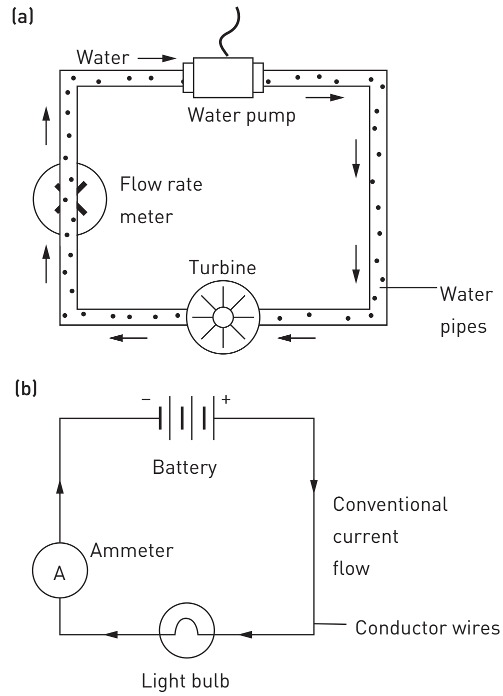

FIGURE 3 (a) A water model can be a useful analogy for (b) the flow of electric charge in a circuit.

Open circuits and electric currents

An electric circuit must be a complete closed-loop path. The charges will flow from the battery through the conductors to the light bulb and deliver the energy given to them by the battery. If the path is not complete, charge will not flow and the current stops. This is called an **open circuit**. Open means the switch is 'off'.

open circuit
an incomplete electrical circuit in which no charge flows

If the battery terminals are connected directly together without the circuit containing a device to restrict the amount of charge flowing (such as a light bulb), then a short circuit occurs. This is a potentially dangerous situation as the very large current that may flow can cause heating of the conductors and subsequent fires. It is possible to cause sparking and welding of the metal conductors when very large batteries are short circuited.

Alternating current

In DC current, the magnitude and direction of the current flow is constant over time. Figure 4(a) illustrates this I–t relationship graphically. However, if the electricity is produced by a generator that uses rotating coils of wire in a magnetic field, it will produce electric currents that vary in both magnitude and direction many times per second. This oscillating type of current flow in a conductor is called alternating current (AC) and is represented graphically in Figure 4(b). Industrial and household electricity is distributed via this type of current flow. The overhead wires on the street outside your home have alternating current.

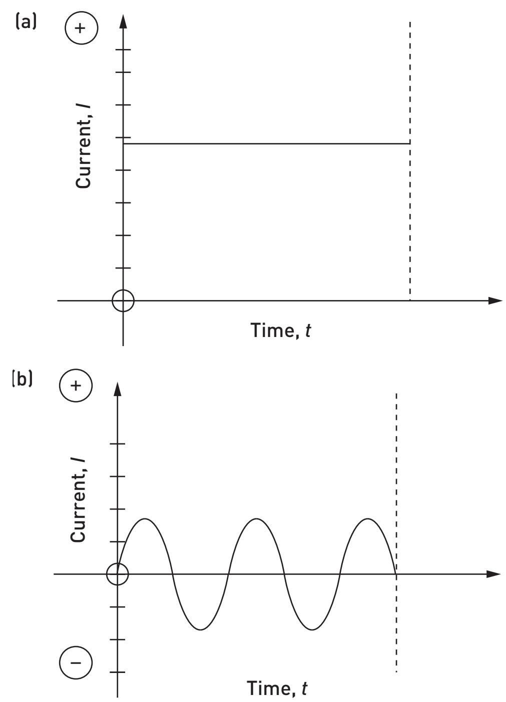

FIGURE 4 (a) In DC current, the magnitude and direction of current flow is constant over time. (b) In AC current, the magnitude and direction of current flow is oscillating or alternating over time.

Measurement of current

When charge moves through a metallic conductor, an electric current is produced. In practice, with electrically charged objects in the laboratory, very large numbers of electrons are moved. Power supplies in your high school laboratory can deliver up to 5 coulombs per second. This is called a current of 5 amperes (5 A) and is measured with an **ammeter**. By definition, if 1 coulomb of electrons passes any given point in a conductor (such as a wire) per second, then a current of 1 ampere (1 A) is passing.

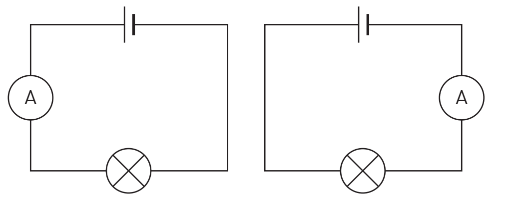

FIGURE 5 An ammeter is connected in series with the circuit device (a bulb in this case). It can be connected on either side of the device. The connecting leads must be connected the correct way; otherwise the pointer on an analogue meter will try to go backwards, and a digital meter will give a negative reading. The positive terminal of the ammeter must be connected to the positive side of the circuit.

ammeter
a device for measuring the rate of flow of charge (current) in a circuit

Ammeters

Ammeters measure the electric current (rate of flow of charge) past a given point, so an ammeter should be connected in **series** with the circuit device (such as a bulb or resistor). There are two types of ammeters available in laboratories: analogue and digital.

series
describes an electrical circuit where components are connected along a single path, so the same current flows through all of the components

Analogue ammeters

Analogue meters have a printed scale and a needle or pointer to indicate the reading. In Figure 6, the analogue ammeter is reading 100 mA. If you said 1 A or 10 mA, you are using the wrong scale. The wire is connected at the bottom to the 500 mA terminal, so you read off the 500 mA scale. On this scale there are 10 divisions for each 100 mA, so the scale reading division is 10 mA. Because of this, the half-scale division is 5 mA, and so the scale reading uncertainty is ± 5 mA.

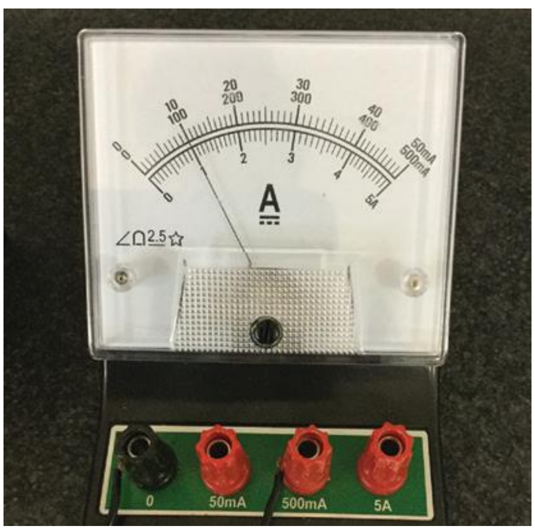

FIGURE 6 An analogue ammeter uses a printed scale and a pointer. The reading on this ammeter is 100 ± 5 mA.

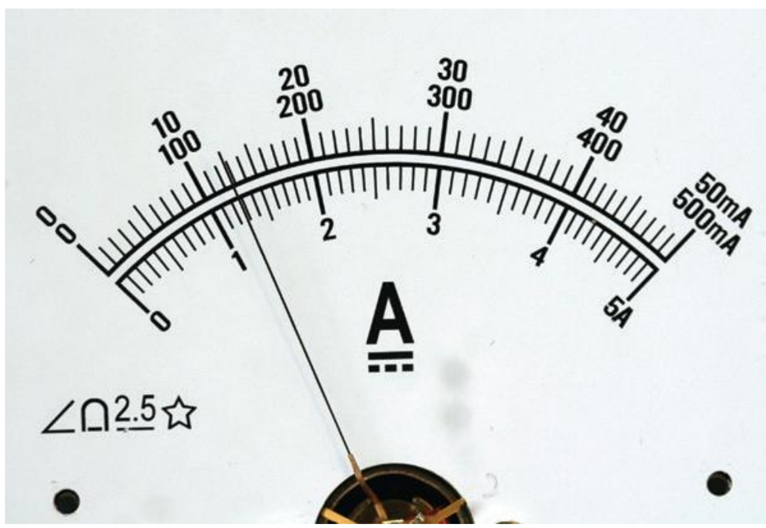

FIGURE 7 An ammeter connected to the 50 mA scale. The reading on this ammeter is 12.5 ± 0.5 mA.

Figure 7 shows an analogue ammeter connected to the 50 mA scale (the top scale). In this case, the pointer is between 12 and 13 mA. The scale divisions are 1 mA apart, so the half-scale divisions are 0.5 mA. When an ammeter pointer is between readings, you must read to the nearest half-scale division, which appears to be 12.5 mA. Thus, our best estimate for the reading in Figure 7 is 12.5 ± 0.5 mA.

Digital ammeters

A multimeter is a more common digital meter as it can be used as an ammeter, voltmeter and ohmmeter (for resistance). The digital meter in Figure 8 has the knob set on the 10 A scale, so the reading on the display is in A (up to a maximum of 10 A). The reading on this multimeter is 0.23 A. The rule for scale reading uncertainty (or 'limit of reading') is ± the final decimal place. Thus, the reading on the meter would be stated as 0.23 ± 0.01 A.

FIGURE 8 A digital multimeter (DMM) being used as an ammeter. The meter is on the 10 A scale, so the reading is 0.23 A. The uncertainty is ± 0.01 A.

Electron speeds

Let's return to conduction in metals and consider a piece of copper wire. The valence electrons within the metallic lattice are moving about at very high speeds in random directions. Chemists call it a 'sea of electrons'. If a voltage is applied through the copper wire by means of a battery across its ends, then the free electrons will move under the repulsion from the negative terminal and be attracted to the positive terminal (Figure 9).

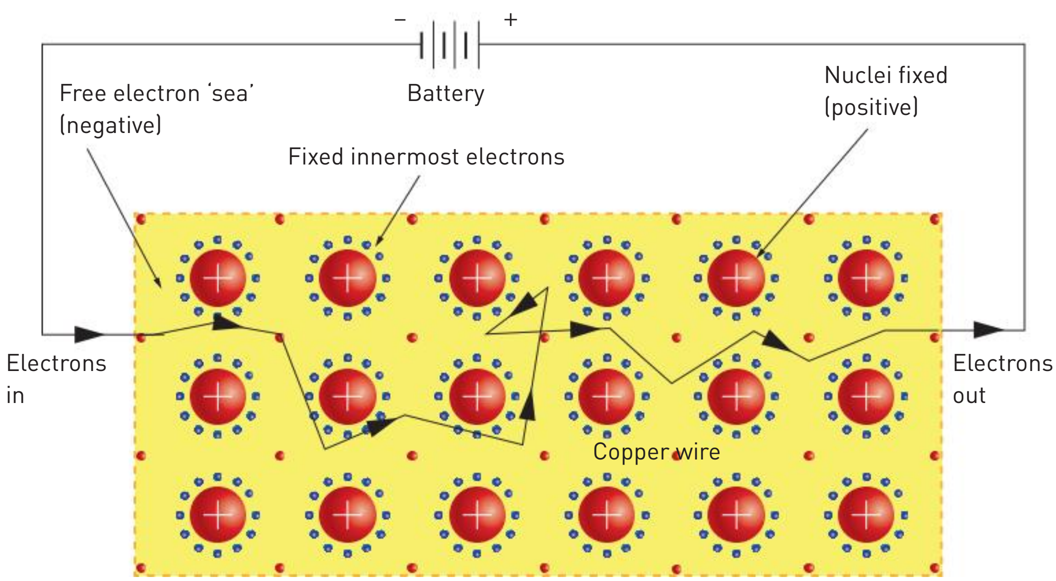

FIGURE 9 Electron motion in a copper wire connected across battery terminals

Because the metallic lattice contains large numbers of nuclei, the electrons in motion undergo collisions that slow their progress. In general, the electrons drift at a particular terminal velocity characteristic of the conductor, which is known as the electron drift velocity, v. Typical metals have values for drift velocities of about 1×10^{-4} m s^{-1}.

FIGURE 10 A multimeter is a common digital meter.

The flow of electric charge (the current) along the wire occurs much more rapidly than the drift velocity of the electrons because an electrostatic repulsive pulse between neighbouring electrons occurs as soon as the electrons begin to move under the influence of the applied electric forces. You can imagine an electron entering one end of the wire and, almost instantaneously, another electron being repelled from the opposite end of the wire. While it is not instantaneous, this occurs at close to the speed of light (3×10^8 m s^{-1}).

CHECK YOUR LEARNING 7.2

Describe and explain

1 **Define** electric current.

2 **Calculate** the electric current in the following cases.
  a A 20 C charge passes through an ammeter in 5 s.
  b A 5 C charge passes through an ammeter in 20 s.
  c A 200 C charge passes through an ammeter in 3 minutes.

3 **Calculate** how many electrons are in a lightning bolt that moves 10.0 C of charge.

4 A torch runs for 1 hour and 6.75×10^{21} electrons flow through the filament.
  a **Calculate** how many coulombs of charge this is.
  b **Calculate** current in amperes for the movement of charge above.

Apply, analyse and interpret

5 **Clarify** what is meant by conventional current.

6 a **Calculate** how many electrons are needed to form a charge of −5.00 nC.
  b **Determine** how many electrons must be removed from a neutral object to leave a net charge of +0.20 μC.

7 When sounding a car horn, the car battery moves 5×10^{20} electrons through the horn. **Determine** how many coulombs of charge were moved.

8 The ammeter in Figure 11 is connected to the 500 mA scale.
  a **Determine** the best estimate reading on the meter. Including the scale reading uncertainty (±) for this scale.
  b **Deduce** the best estimate and uncertainty for the reading if the ammeter was connected to the 50 mA scale.

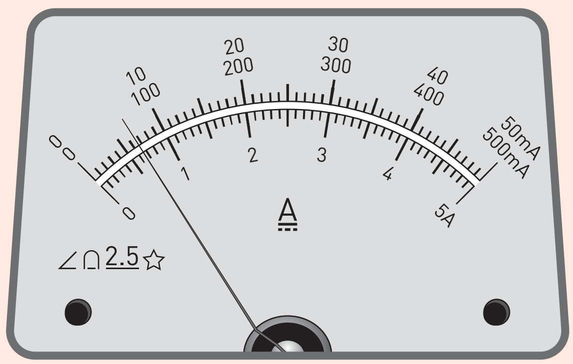

FIGURE 11 Use the 500 mA scale

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Direct current

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Conventional current

7.3 Voltage and sources of potential energy

KEY IDEAS

In this section, you will learn about:

- electric potential and electric potential energy.

In an electric circuit, the battery provides potential energy to electrons, and devices such as bulbs and resistors transform that energy to other forms such as heat and light. Electrical energy is very important in our lives. The great explosion in technology in the twentieth century has been almost solely due to applications of electrical energy. Our information age would not be possible without electricity flowing through wires.

Electric potential and electric potential energy

The gravitational model is a good analogy to describe energy stored between charges. Imagine a 1 kg block of wood on a bench. The pull of gravity between the block and Earth is defined as being downward (as the block appears to be pulled down). When you lift the block up against gravity, you need to do work on the block (from your muscles) and the energy gets transferred to the block-and-Earth system. We say the block has acquired more gravitational potential energy (GPE).

This increase in gravitational potential energy is equivalent to the work done (W) and is calculated using $W = mgh$. Similarly, with electricity, it requires work (W) to be done to pull a positive charge away from a negative charge. The work done is given by:

$$W = QEd$$

where E is a measure of the electric field strength (just as the acceleration due to gravity, g, is a measure of gravitational field strength), d is distance (similar to height), and W is the increase in electric potential energy.

electric potential
the amount of work needed to move a unit (1 C) of charge from one point to another, or the electric potential energy per unit of charge (symbol: *V*; SI unit: volt; unit symbol: V).

electric potential energy
the energy stored in a charge; or the capacity of the charge carriers to do work due to their position in an electric circuit (symbol: *U*; SI unit: joule; unit symbol: J).

If we do 1 joule of work (W) on 1 coulomb of charge (Q), we can say that we have increased the **electric potential** (V) of the charge by 1 volt. We can also say we have increased the charge's **electric potential energy** by 1 joule. The charge can use this energy to do work. We can also apply this to an electric circuit of cells and wires.

If it took 10 J of work to shift a 2 C charge from A to B, we would say its electric potential energy has changed by 10 J, but that its electric potential has changed by 5 joules per coulomb (5 J C^{-1}, or 5 V). This is a subtle but critical difference.

$$\text{Electric potential} = \frac{\text{work}}{\text{charge}}$$

$$V = \frac{W}{Q}$$

Electric potential (V) is a scalar quantity and is measured in units of joules per coulomb (J C^{-1}). One joule per coulomb is also known as a volt: 1 volt (V) = 1 J C^{-1}.

Electric potential defines a region of space or position in a circuit irrespective of whether there is any charge there or not. It just says that if there was charge at that point it would have this electric potential value. Electric potential energy refers to the energy in the charge that is actually there.

potential difference the difference in electric potentials between two points in an electric field

TABLE 1 Units and symbols related to electric potential

Quantity	Quantity symbol	Unit	Unit symbol
Electric potential	V	volt	V
Electric potential energy	W	joule	J

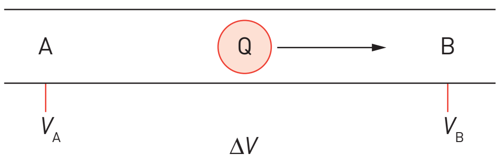

FIGURE 1 Moving a charge Q from A to B

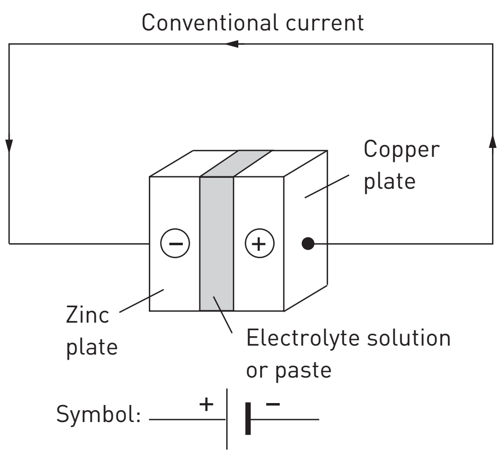

FIGURE 2 A copper–zinc cell

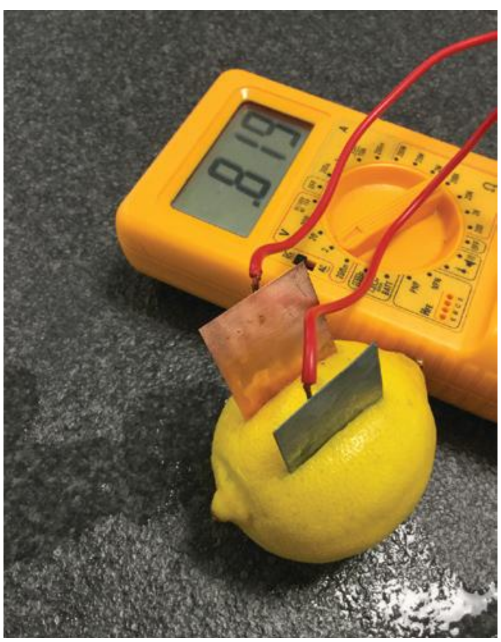

FIGURE 3 You can get electrical energy out of a circuit that uses a lemon with a piece of copper and a piece of zinc, but it's not practical to use it to power a phone or a dishwasher.

Potential difference

Potential difference (p.d.) is the difference in electric potentials between two points in an electric field (that is, a region where electric forces can be experienced). Imagine a charge Q being moved from point A to point B (Figure 1) by doing work on it.

The p.d. is the difference between the two electric potentials and has the symbol ΔV. It is common to assign one of the points as zero potential, so instead of ΔV we can just use V for potential difference.

Potential differences become useful in electrical circuit work (to be discussed in the next chapter). If the two ends of an electrical conductor are held at different potentials (such as by connecting to the opposite poles of a battery), then a potential difference is set up across the conductor. The subsequent electric field within the conductor will allow free electrons to flow. This is the electric current within the conductor.

Sources of electric potential

In the previous section we said that a battery can supply direct current (DC). Let us take this idea further to see why this is possible. A simple cell consists of two dissimilar metals separated by a conducting solution. The familiar carbon–zinc dry cell (carbon = positive, zinc case = negative) produces a potential difference of about 1.5 V.

Chemical reactions in a copper–zinc cell (Figure 2) cause the copper electrode to become positively charged and the zinc electrode to become negatively charged with a potential difference of about 1.0 V.

When a simple cell is constructed, the metal plates are separated by a salt solution or a conducting paste. The electric potential difference still exists between the positive and negative metal electrodes of the cell. This potential difference is measured in volts (V) and is usually referred to as the **electromotive force (EMF)** of the cell, or simply its voltage.

The EMF represents energy per unit charge (voltage) that has been made available by the generating mechanism. It is not a 'force'. The common term 'voltage' can refer to one of two distinct physical ideas: EMF or potential difference. EMF is associated with sources of electrical energy, while potential difference is used to describe changes around a circuit. The symbol EMF is retained for historical reasons.

Internal energy and electric potential energy in a cell

In Chapter 1 you saw that internal energy is the sum of microscopic forms of energy including the bonds between and within chemicals. Electric potential energy is therefore a part of the cell's internal energy. A fully charged battery will have more internal energy than a flat battery.

electromotive force (EMF)
a difference in electric potential that produces an electric current (symbol: EMF; SI unit: volt; unit symbol: V)

Combination of cells

If several simple cells are joined together, the combined arrangement is called a battery. A normal 12-volt car battery usually has six individual cells, each of 2 V, connected together in series. Notice that the battery symbol (Figure 4, top) actually consists of four separate cells connected together so that positive electrodes are directly connected to negative electrodes. This type of connection is called a **series connection** of the cells, and the total EMF is the sum of the EMFs of each cell.

series connection
one in which the components are connected along a single path

Series connection:
total EMF = sum of individual cells, EMFs

Individual cells may also be connected so that all positive electrodes are connected together and all negative electrodes are connected together. This is called a parallel connection, and the total EMF is then the same as that of each individual cell. In a parallel connection, a battery cannot supply more energy to each electron. However, it can supply a greater quantity of electrons per unit time or a greater current flow in any external circuit (Figure 4, bottom).

Parallel connection:
total EMF = individual cell EMF

Note that only cells with equal values of EMF should be connected in parallel.

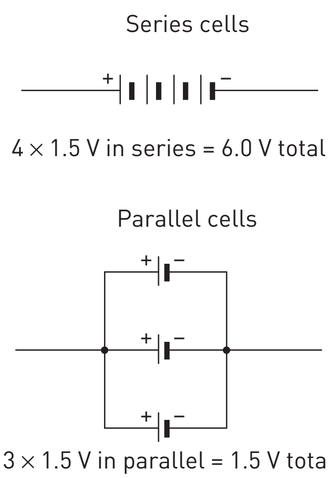

FIGURE 4 Cells in a series connection provide greater EMF than cells in a parallel connection.

parallel connection
one in which the components are connected along multiple paths

Changes in electric potential in a circuit

Once several cells are connected together and a battery is produced, the device can be used to provide electric current in an external circuit by connecting the positive and negative terminals (Figure 5). The battery itself is the energy pump that raises the charge to a higher electric potential at the positive terminal. Positive conventional current will flow from the positive terminal of the battery, through the external circuit conductors, and back to the negative battery terminal. Along this pathway the charge loses electric potential as it does work in various

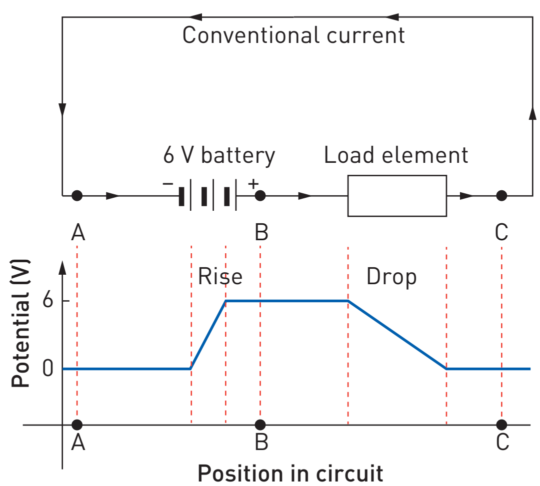

FIGURE 5 The battery provides the electric current for the circuit; the positive conventional current will flow from the positive terminal, through the circuit and back to the negative terminal. During this process, some potential energy will be converted to other forms of energy.

Study tip

If you were asked to compare the EMFs of two cells, what would you say? 'Compare' means to state the similarities and differences and their significance. You would need to state the **similarity** that one end of each cell was positive and the other end negative, and the **difference** being the voltage value of each cell with reference to the negative end.

circuit elements such as resistors, bulbs and motors.

In the circuit, potential energy of the charge is converted to other forms of energy such as thermal, kinetic or light energy. In this process of energy conversion, the charge is not destroyed or used up – its electric potential energy is reduced back to zero as it reaches the negative battery terminal. The battery will restore the electric potential energy of the charges back again to a high value.

This is similar to lifting a ball in the air. As you lift the ball, you increase its potential energy (like a battery). When the ball falls, its potential energy decreases. The ball still exists (like the charge does), but it has reduced potential energy. Strictly speaking, it is the ball–Earth system that stores the energy, not just the ball. Likewise, electrical potential energy is stored in the system of positive and negative charges, not just the one charge flowing in the circuit. To make it simpler, we just say Earth has zero joules of gravitational potential and the negative terminal of an electric cell has 'zero volts' of electric potential.

Study tip

You may be asked to 'distinguish' between series and parallel circuits. This means you should be able to recognise them as different and note points of difference between them. The main difference is the way they are connected: **series** means they are joined positive to negative, whereas **parallel** means the positive terminals are connected together and the negative terminals are connected together.

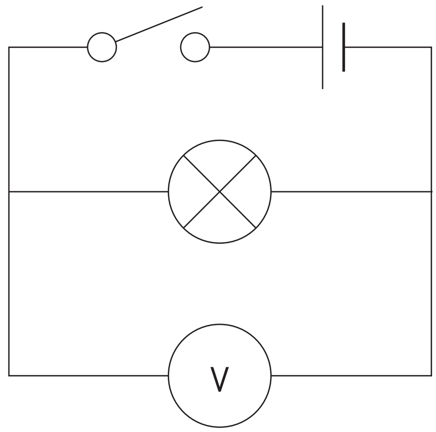

FIGURE 6 The voltmeter is connected in parallel with a circuit device such as a bulb – the voltmeter is connected 'across' the device.

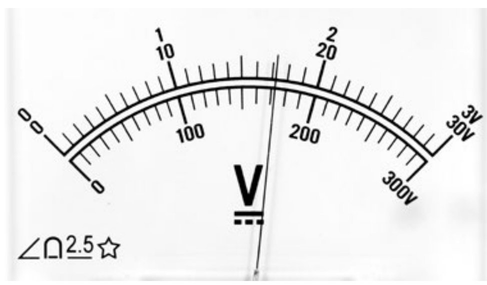

FIGURE 7 The voltmeter was set to the 30 V scale, and the reading is 17.0 ± 0.5 V.

voltmeter
an instrument used for measuring electrical potential difference between two points in an electric circuit

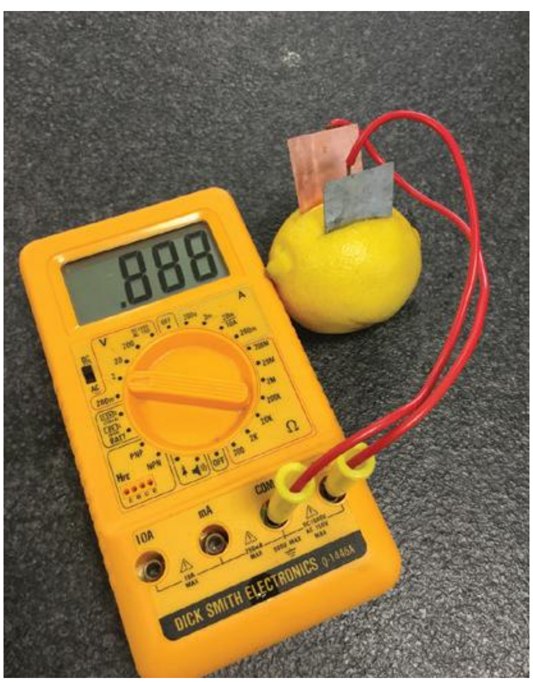

FIGURE 8 A digital multimeter set to read voltage. This reading would be stated as 0.888 ± 0.001 V.

Measurement of voltage

Voltmeters

A **voltmeter** is used to measure the voltage difference in a circuit. Reading a voltmeter is similar to reading an ammeter. However, a voltmeter measures the potential difference **between** two points in a circuit, so it must be connected 'across' (one lead either side of a circuit device such as a bulb). A voltmeter is connected in parallel with a circuit device.

Analog voltmeters

The voltmeter in Figure 7 is connected to the 30 V scale. The scale division is 1 V, so the half-scale division is 0.5 V. Similar to an ammeter, it is usual to read to the nearest half-scale division. Close inspection suggests the needle is closer to 17.0 V than 17.5 V, so our 'best estimate' is 17.0 ± 0.5 V.

Digital voltmeters

As with digital ammeters, digital voltmeters have the same rule for their uncertainty – the uncertainty is the last decimal place to the right, which is the least significant decimal place. The digital voltmeter connected to a lemon in Figure 8 has the knob set to the 2 V scale, so any reading is in volts (not mV). Thus, the reading is 0.888 V. The uncertainty is 0.001 V, so the 'best estimate' is 0.888 ± 0.001 V.

FIGURE 9 This torch bulb is labelled '4.8 V, 0.3 A' – it is designed to give a sustained maximum brightness at 4.8 V, at which it will 'draw' a current of 0.3 A.

Case study 7.3

Light bulbs, volts and current

Torch bulbs are a common circuit element used in physics laboratories. If you check the label, the bulb will have a voltage and current rating. A bulb labelled '12 V, 2 A' means if you connect the bulb across a 12 V DC electricity supply it will 'draw' a current of approximately 2 A. You can run the bulb at a lower voltage, but at 6 V it won't draw just 1 A. The response curve is not linear. The bulb is hotter at higher voltages, and this increases its resistance and as a result it draws less current. Over 12 V and you will probably 'blow' the bulb.

CHECK YOUR LEARNING 7.3

Describe and explain

1 **Define** electric potential energy.

2 **Describe** how electric charge separation produces an electric potential difference.

3 **Calculate** the voltage if 60 J of energy is available for every 15 C of charge.

4 When 15 C of charge is moved between two points in an electric field, 20 J of work is done. **Calculate** the potential difference between the two points.

Apply, analyse and interpret

5 A charge of 2.00 C of charge passes through a pocket calculator's solar cells in 2.00 h. Given the calculator's voltage output is 4.5 V, **determine** the work done.

Investigate, evaluate, and communicate

6 You have three cells, each with a voltage of 2 V.

a **Propose** how you would arrange them to produce:

i 6 V

ii 2 V.

b **Judge** the advantage of using three 2 V cells in parallel rather than just one 2 V cell by itself considering they give the same voltage.

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» Increase your knowledge
Voltage sources of potential energy

» Weblink
Lighting

7.4

Power

KEY IDEAS

In this section, you will learn about:

+ power and its equations.

power
the rate at which work is done or the rate at which energy is transferred or transformed

You often hear about one thing being more powerful than another. But what do we mean by **power**? For example, a student walks up a flight of stairs one day but the next they run up them. In which case do they use more energy, and in which case do they have a bigger power output? The answer is that they use the same energy in each case because their gravitational potential energy ($E_p = mgh$) is the same. However, when the student runs up the stairs they use the energy in a shorter amount of time, so we say they had a higher power output.

Power formula

Power can be expressed as an equation:

$$\text{Power (in watts, W)} = \frac{\text{work (in joules, J)}}{\text{time (in seconds, s)}}$$

$$P = \frac{W}{t}$$

Units and symbols related to power often confuse students as the letter 'W' represents two things, as shown in Table 1. The symbol W is used for the quantity **work** (in italics, W), and also for the unit **watt**. For example:

Work = 1000 joules (W = 1000 J); Power = 50 watts (P = 50 W)

TABLE 1 Units and symbols related to power

Quantity	Quantity symbol	Unit	Unit symbol
Work (energy)	***W***	joule	J
Power	*P*	watt	**W**
Time	*t*	second	s

Common multiples of the watt in electrical circuits are milliwatts (mW) and kilowatts (kW). For power stations, the multiples are megawatts (MW) for a million (10^6) watts, and gigawatts (GW) for a billion (10^9) watts. Power consumption in electrical circuits will be discussed in Chapter 9.

WORKED EXAMPLE 7.4A

An electric heater has a power of 2 kW.

a Determine the power of the heater in watts.

b Calculate how much energy the heater will use in 10 minutes.

SOLUTION

a P = 2 kilowatts = 2000 watts

b $P = \frac{W}{t}$

$W = Pt = 2000 \times (10 \times 60) = 1\,200\,000$ J (or 1.2 MJ)

Additional power formulas

$P = \frac{W}{t}$, so $P = \frac{VQ}{t}$ (as $W = VQ$ from the rearrangement of $V = \frac{W}{Q}$ from Section 7.3).

However, we also know that $I = \frac{Q}{t}$, so our formula for power becomes:

$$P = VI$$

We can also combine $P = \frac{W}{t}$ and $P = VI$ to give $\frac{W}{t} = VI$. This can be rearranged to give:

$$W = VIt$$

WORKED EXAMPLE 7.4B

Determine the flow of current in a toaster that has a power rating of 1200 W and is connected to the 240 V home supply.

SOLUTION

$P = VI$

$I = \frac{P}{V} = \frac{1200}{240} = 5\ \text{A}$

WORKED EXAMPLE 7.4C

Calculate how many joules of electrical energy are transferred per second by a 6 V, 0.5 A lamp.

SOLUTION

$W = VIt$

$= 6 \times 0.5 \times 1$

$= 3\ \text{J}$

CHECK YOUR LEARNING 7.4

Describe and explain

1 **Define** power.

2 **Calculate** the power consumption of a lamp labelled as '12 V, 2 A'.

3 **Calculate** how many watts are used by a torch that has 6.00×10^2 C pass through it in a half-hour if its voltage is 4.5 V.

4 **Calculate** how much energy is produced by a lightning bolt having a 20 kA current, a voltage of 125 MV and a duration of 2.00 ms.

Apply, analyse and interpret

5 A 10 W night light is on from 6 p.m. to 6 a.m. **Determine** how much electrical energy it uses.

6 **Deduce** how much electrical energy is needed to make a slice of toast with a 1200 W toaster if the cooking time is 1 minute.

7 **Deduce** the power consumption in kilowatts for Queensland's old train network that ran at 1500 V DC. Typically, under full acceleration, a train would draw 250 A.

8 A car starter motor draws a huge current as it must spin the engine to get it started. It takes 5 seconds to start the engine. Typically, a starter motor draws an initial current of 150 A from a 12 V DC battery. **Determine** the:

a power consumption

b amount of energy used in the time it takes to start the engine

c amount of charge (in coulombs) passing through the wire in the 5 s

d the number of electrons leaving the battery in the 5 s.

9 It takes 168 kJ to heat 500 mL of water (2 cups) from 20°C to 100°C. **Determine** how long would it take an electric kettle to do this if it has a power output of 2000 W.

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CHAPTER 7

Review

Summary

7.1

- All matter is made up of atoms that contain electrically charged protons (positive) and electrons (negative), as well as neutrons (neutral).
- Materials can become electrically charged by gaining or losing electrons. This may be caused by friction or rubbing processes, or by charge sharing.
- Electric charge can be positive or negative – positive if it has lost electrons and negative if it has gained electrons. Opposite charges attract and like charges repel.
- Charge is a quantity of electricity measured in coulombs. The charge on one electron is 1.60×10^{-19} C.
- Insulators do not allow electricity to flow through them, whereas conductors do. Semiconductors are modern materials whose conductivity can be controlled.
- Charge will remain where placed onto an insulator material, such as a plastic rod, but will distribute itself across the surface of a conductor material, such as a metallic solid.
- The law of conservation of charge states that electric charge can neither be created nor destroyed. The net quantity of electric charge (the amount of positive charge minus the amount of negative charge in the universe) is always conserved.

7.2

- Electric current is carried by discrete electric charge carriers.
- Electric current can be described as either conventional (positive) current or electron (negative) flow.
- Conventional current has been accepted as the international convention. Consistent use now ensures clear communication of ideas and findings around the world.

7.3

- The electromotive force (EMF) of a battery is the energy transferred per coulomb of charge within the battery. EMF is measured as a voltage in volts.
- The energy available to electric charges moving in an electrical circuit is measured using electric potential difference.
- Electric charge separation produces an electric potential difference.
- Potential differences within a circuit are referred to as a potential rise when produced by an EMF source, or as a potential drop when caused by a load element. Potential differences are also measured in volts.
- Electrical power, measured in watts, is the rate at which electrical work is done in a circuit and can be calculated using $P = \frac{W}{t}$.
- Potential difference is measured using a voltmeter. Current is measured using an ammeter.
- A cell or battery is said to be a source of EMF.
- There are two types of connections: series connection and parallel. Series is one in which the components are connected along a single path. For cells it is one in which positive and negative cells are connected; A parallel connection is one in which the components are connected along multiple paths. For cells it is one in which all the positive terminals of the cells are connected together, and all the negative terminals are connected together.

Key terms

- ammeter
- charge
- conductors
- conventional current
- coulomb
- electric current
- electric potential
- electric potential energy
- electromotive force (EMF)
- elementary charge
- insulators
- ion

- law of conservation of charge
- open circuit
- potential difference
- power
- series
- voltage
- voltmeter
- volts

Key formulas

Electric potential	Electric potential $= \frac{\text{work}}{\text{charge}}$ $V = \frac{W}{Q}$
Elementary charge	Number of elementary charges $= \frac{\text{charge in coulomb}}{\text{elementary charge}}$ $n = \frac{Q}{q_e}$
Electric current	Electric current $= \frac{\text{charge in coulomb}}{\text{time elapsed}}$ $I = \frac{Q}{t}$
Power	Power $= \frac{\text{energy}}{\text{time}}$ = voltage × current $P = \frac{W}{t} = VI$

Revision questions

The relative difficulty of these questions is indicated by the number of stars beside each question ★ = low; ★★ = medium; ★★★ = high.

Multiple-choice

1 The free electrons of a metal:
- A do not collide with each other.
- B are free to escape through the surface.
- C are free to fall into the nuclei.
- D are free to move anywhere in the metal.

2 When there is an electric current passing through a wire, the particles moving are:
- A electrons.
- B protons.
- C atoms.
- D ions.

3 The current flowing through a conductor, when 2×10^7 electrons pass in 1 μs, will be:
- A 1.6×10^{-6} A
- B 3.2×10^{-6} A
- C 4.2×10^{-6} A
- D 6×10^{-6} A

4 The amount of charge flowing through a cross-sectional area of a wire per unit of time is called:
- A voltage.
- B power.
- C resistance.
- D current.

5 Which of the following is **not** a valid conclusion about electric current in a conductor?
- A Electric charges move because of an electric field throughout a circuit.
- B The electric field is produced by a source of energy that moves charges.
- C The electric field is established at near the speed of light in a circuit.
- D Electric charges move very fast in response to the electric field.

Short answer

Describe and explain

★ 6 **Define** the law of conservation of charge and clarify with an example.

★ 7 **Recall** an example of a ‘discrete charge carrier’ and explain what the term means.

★ 8 **Explain** how the law of attraction and repulsion can be demonstrated.

★ 9 **Recall** the SI units and symbols for charge, time, current, energy, electric potential, EMF and power.

★ 10 **Define** electric current, electric potential, electrical potential energy, EMF and power.

★ **11** **Explain** the difference between electric potential and electric potential difference.

★ **12** **Identify** what corresponds to the charge and what corresponds to the current when traffic flow is used as an analogy for electric current.

★ **13** **Calculate** how many coulombs of charge are involved in a chemistry experiment in which 4×10^{24} electrons pass into a solution of silver chloride.

★ **14** **Calculate** how many elementary particles are involved when a plastic rod is rubbed with fur and an electrometer measures 1.5 μC of charge present on one end.

★ **15** **Calculate** the electric current in the following cases.

- **a** A 20 C charge passes an ammeter in 1 minute and 30 seconds.
- **b** A 5 μC charge passes an ammeter in 3.0 s.
- **c** A 200 C lightning bolt travels to the ground in 0.5 seconds.

★★ **16** **Explain** why a charge of 2×10^{-20} C is not possible.

★★ **17** **Calculate** the increase in electric potential (voltage) produced by a cell if every 2.6 C of charge passing through is supplied with 3.9 J of energy.

★★ **18** **Calculate** how many electrons pass out every second from a 12.0 V car battery that runs a single 30.0 W headlight.

★★ **19** Two points in space are at electric potentials of +18 V and −6 V respectively.

- **a** **Calculate** the potential difference between these points.
- **b** **Calculate** the work done in moving a charge of 5.5 μC from one point to the other.

★★ **20** In one particular lightning flash, the potential difference between the two ends of the lightning bolt was 10^9 V and the quantity of charge transferred was 10 C. **Calculate** how much energy was released.

★★ **21** In moving an electron from point X to point Y along a uniform field, a total of 2×10^{-20} J is done. **Calculate** the potential difference between X and Y.

★★★ **22** A battery-powered busker's amp is a portable amplifier that runs on six 1.5 V AA batteries in series (total 9 V). When turned to full volume, the amp draws a current of 235 mA. **Calculate** the:

- **a** power consumption
- **b** amount of energy used for a 2-minute song at maximum output
- **c** amount of charge (in coulombs) passing through the wire in the 2 minutes
- **d** number of electrons leaving the battery in the 2 minutes.

Apply, analyse and interpret

★ **23** **Clarify** the relationship between charge and current.

★ **24** **Classify** electric charge into two types and **explain** what 'classify' means.

★ **25** **Determine** whether the internal energy of a battery is different when it is flat to when it is fully charged, and **explain** your answer.

★ **26** **Determine** how long it would take for 12 C to pass through a salt water solution at a current of 2.5 A.

★★ **27** **Deduce** whether an electron is 'matter'. **Explain** how you know.

★★ **28** **Determine** the voltage necessary to move 15 C of charge through a conductor if the energy required is 80 J.

★★ **29** An atom of iron has 26 protons, 30 neutrons and 26 electrons. Electrons are removed, and the atom acquires an overall +3 charge. **Deduce** how many electrons are left in the atom.

★★ **30** An electric current of 3.5 A passes through a salt solution for a period of 5 minutes. **Determine** how many coulombs of charge pass into the solution.

★★★ **31** A piece of metal conductor is estimated to contain 3×10^{22} electrons per metre of its length and it carries a current of 1.5 A. **Determine** the average drift velocity of the electrons in the conductor

★★★ **32** An electron volt (eV) is defined as the amount of work done to move an electron ($q_e = -1.60 \times 10^{-19}$C) through a potential difference of 1.0 V. **Determine** the value of the electron volt (eV) in joules.

★★★ **33** **Determine** how much energy is required to move an electron from a p.d. of −6 V to a p.d. of +10 V.

★★★ **34** An amp is able to put out 25 W of power from eight AA 1.5 V batteries in series for a total of 10 hours before the batteries are 'flat'. **Determine** how many joules of energy are produced by each battery before going flat.

Investigate, evaluate and communicate

★★ **35** **Develop** a definition for the term 'phenomenon' from the following example: When you comb your hair and it crackles, it is said to be a phenomenon associated with electric charge.

★★ **36** **Predict** which uses the greater amount of power: a motorcycle headlight that draws 10 A from a 6 V battery, or a car parking light that draws 6 A from a 12 V battery.

★★ **37** Positrons are positive electrons and are sometimes called an 'antielectron'. They have the same mass as an electron but opposite charge. Imagine an electron and an antielectron (+q_e) collide and turn into a photon of light energy which has no charge (Figure 1). **Justify** how this supports the law of conservation of charge.

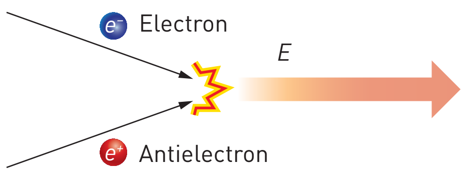

FIGURE 1 An electron and antielectron met at a party.

★★ **38** A meter is shown in Figure 2.

- **a** **Predict** the reading on this meter to the nearest half-scale division (including its scale reading uncertainty.
- **b** **Propose,** and **explain** your reasoning, whether it is connected in series or parallel.

FIGURE 2 A meter in a circuit

★★ **39** A meter that is part of a circuit is shown in Figure 3.

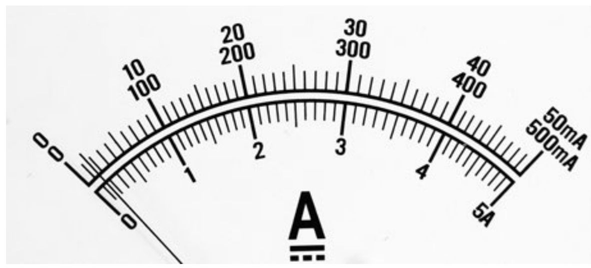

FIGURE 3 This meter is set to the 5 A scale

- **a** **Determine** the reading on the meter (on the 5 A scale) to the nearest half-scale division (including its uncertainty).
- **b** **Discuss** whether you could get a more accurate reading by changing over to one of the other scales.
- **c** A student claimed that this was a multimeter because it had multiple scales. **Justify** whether this is an ammeter or a multimeter.

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CHAPTER 8

Resistance

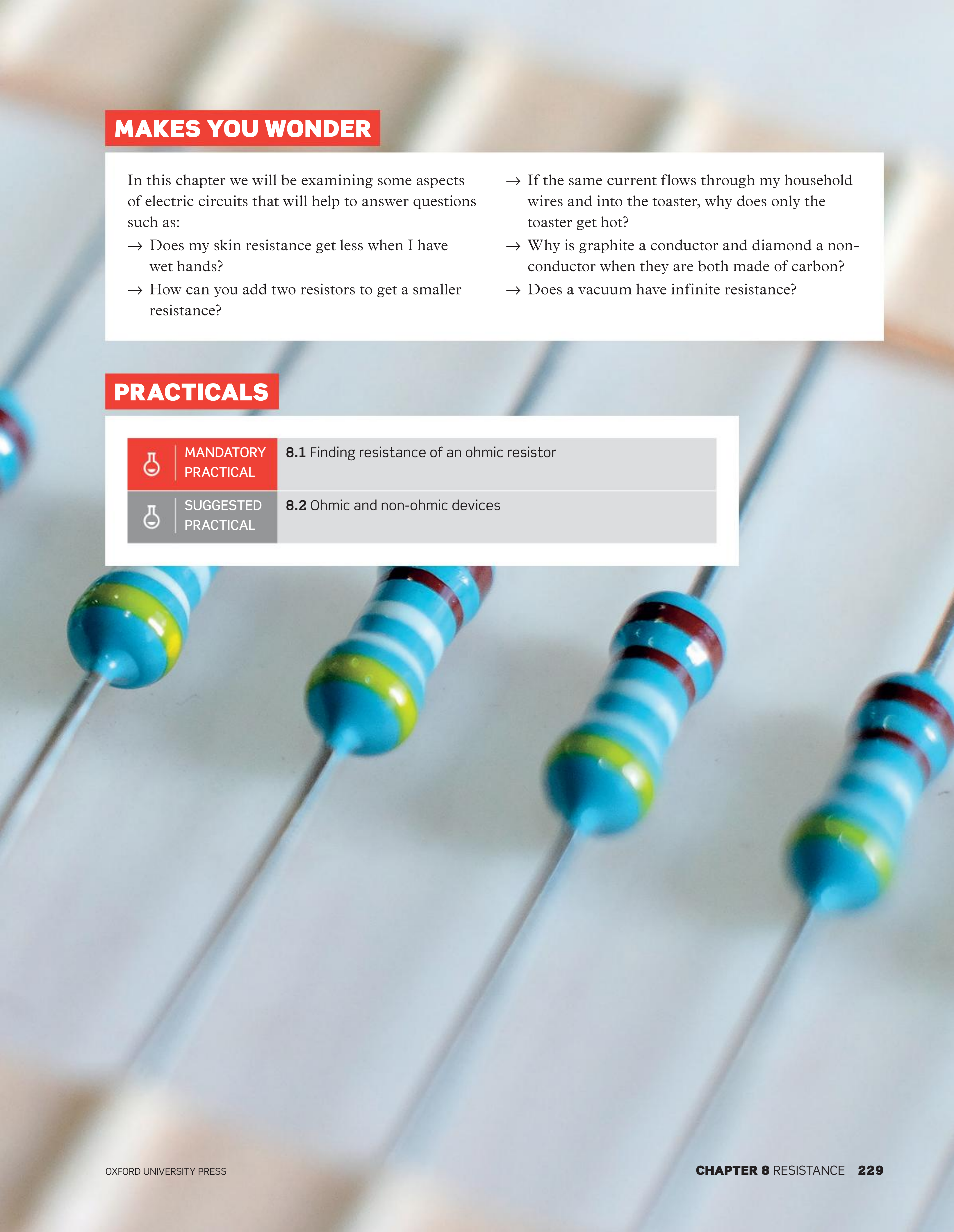
We can divide matter into two categories: conductors and insulators. Conductors have low resistance to the flow of charge, and insulators have high resistance. But some metals are better conductors than others, and you can blend metals to change their resistance. In this chapter we will investigate 'resistance'. An analogy for resistance is water coming out of a hose – putting some steel wool up the hose would reduce the flow of water. The steel wool would increase the resistance to the flow of water inside the hose and slow it down.

OBJECTIVES

→ Define resistance.
→ Recall and solve problems using Ohm's law.
→ Compare and contrast ohmic and non-ohmic resistors.
→ Interpret the Ohm's Law graphical representations of electrical potential difference versus electric current data to find resistance using the gradient and its uncertainty.

Source: *Physics 2019 v1.2 General Senior Syllabus Queensland Curriculum & Assessment Authority*

FIGURE 1 Resistors are devices that reduce the flow of charge in a circuit.



MAKES YOU WONDER

In this chapter we will be examining some aspects of electric circuits that will help to answer questions such as:

→ Does my skin resistance get less when I have wet hands?

→ How can you add two resistors to get a smaller resistance?

→ If the same current flows through my household wires and into the toaster, why does only the toaster get hot?

→ Why is graphite a conductor and diamond a non-conductor when they are both made of carbon?

→ Does a vacuum have infinite resistance?

PRACTICALS

MANDATORY PRACTICAL	**8.1** Finding resistance of an ohmic resistor
SUGGESTED PRACTICAL	**8.2** Ohmic and non-ohmic devices

8.1 Resistance

KEY IDEAS

In this section, you will learn about:

+ the definition of resistance
+ factors that affect resistance.

When a battery is connected to the ends of a metal wire, it applies a potential difference, V, that creates an electric field from one end to the other. The electric field in turn exerts a force on the electrons in the wire, causing an electric current. Although the electrons are accelerated by the applied electric field due to their small mass, they very quickly collide with the lattice of positive metal ions in the conductor and lose energy. The effect of the collisions within the lattice is to reduce the current. Every time an electron collides with one of the metal ions in the lattice, it loses energy, which is transferred to the lattice as heat and vibrational energy – as internal energy. This means the temperature of the conductor increases.

This opposition to the flow of electric current that any conductor produces is called its **electrical resistance**. The larger the resistance, the smaller the current that flows as a result of any given applied voltage.

electrical resistance
opposition to the flow of electric current in a circuit measured as the ratio of the voltage applied to the electric current that flows through it

$$R = \frac{V}{I}$$

Resistance is measured in the unit **ohm**, named after German physicist Georg Simon Ohm (1787–1854). Its symbol is the Greek letter omega (Ω). For example, the resistance of a heating element in a toaster is about 48 Ω.

Factors affecting resistance

Three factors determine the resistance of a conductor: length, area and material. The first two are related to shape.

Length

The longer the length (L) of a conductor, the greater the number of collisions occurring and therefore the greater the resistance. Mathematically, resistance is found to be directly proportional to the length ($R \propto L$).

Cross-sectional area

The smaller the cross-sectional area (A) of a conductor, the less space the electrons have for movement and hence the greater the resistance. Mathematically, the resistance is inversely proportional to the cross-sectional area $\left(R \propto \frac{1}{A}\right)$.

Table 1 shows classroom results for the resistance (R) of some nichrome wire of different length (L) and diameter (d). Standard wire gauge (SWG) is related to the wire's diameter – bigger diameter means smaller gauge.

TABLE 1 Classroom resistance results for different (a) lengths and (b) area

(a)

L (cm)	R (Ω)
30	0.9
60	1.9
90	2.8

(b)

SWG	d (mm)	A (× 10^{-7} m²)	$\frac{1}{A}$ (× 10^{7} m⁻²)	R (Ω)
26	0.43	1.5	0.69	8.3
24	0.56	2.5	0.41	5.0
22	0.71	4.0	0.25	3.1

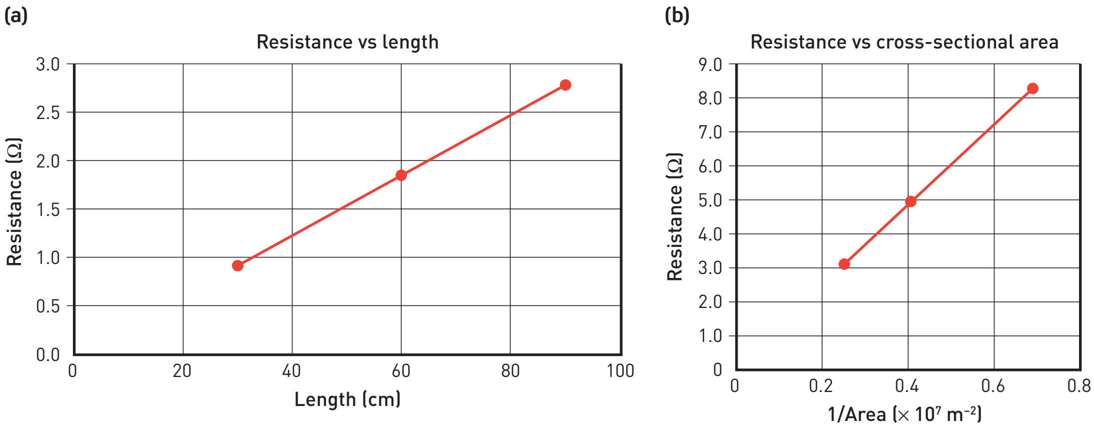


FIGURE 1 (a) Length and resistance vary in direct proportion. (b) When the resistance of three different gauges (thicknesses) of nichrome wire (1.0 m long) is plotted against the reciprocal of their cross-sectional area, a linear graph is obtained. This confirms that $R \propto \frac{1}{A}$.

Material

The third factor affecting resistance is material. Different types of metals will have varying lattice types. For example, nichrome wire heats up more than copper wire. It is harder for the current to flow through the nichrome because it is an alloy of two metals: nickel and chromium. These metals are slightly different from each other. As a result, instead of the electrons flowing smoothly through the material, the electrons frequently bounce off the unevenness that the mixed-up nickel and chromium atoms make.

If the atomic lattice is irregularly or tightly packed, more collisions are likely, and more energy is lost by the charge – thus, the greater is the resistance.

For non-metals, the resistance depends on how strongly the electrons are held in bonds. In covalent bonds, such as in plastic and ceramics, the electrons are held very tightly. In graphite, this is less so. Materials that provide high resistance to current are said to have greater resistivity.

Summary

Resistance is dependent on shape and material. Resistance will be **greater** if:

- length (L) is increased
- cross-sectional area (A) is decreased
- lattice is irregular or tightly packed, or electrons are tightly held in bonds (increasing what is known as resistivity).

Resistivity

As mentioned above, the type of material from which any conductor is made controls the property called the **resistivity**, ρ (pronounced 'rho').

The overall electrical resistance, R, is given by:

$$R = \rho\frac{L}{A}$$

where ρ = resistivity (measured in Ω m), L = length (measured in m) and A = cross-sectional area (measured in m^2).

resistivity
a fundamental property of matter that quantifies how strongly a given material opposes the flow of electric current

Study tip

Temperature does affect resistance. That's why resistivity is quoted for a particular temperature.
For most metals, resistance increases with increasing temperature. More information on this can be found on your obook assess.

TABLE 2 Resistivity for some common materials

Material	Resistivity, ρ (Ωm) at 20°C
Carbon (graphene)	1.0×10^{-8}
Silver	1.5×10^{-8}
Copper	1.7×10^{-8}
Gold	2.4×10^{-8}
Aluminium	2.6×10^{-8}
Tungsten	5.6×10^{-8}
Nickel	7.0×10^{-8}
Iron	8.9×10^{-8}
Platinum	9.8×10^{-8}
Chromium	12.5×10^{-8}
Carbon steel	14.3×10^{-8}
Titanium	42.0×10^{-8}
Manganin	48.2×10^{-8}
Constantan	49.0×10^{-8}
Stainless steel	69.0×10^{-8}
Mercury	98.0×10^{-8}
Nichrome	100×10^{-8}
Sea water	0.2
Drinking water	20–2000
Silicon	6400
Glass	1.00×10^{11} to 1.00×10^{15}
Fused quartz	7.50×10^{17}

WORKED EXAMPLE 8.1

Calculate the resistance of a 4.0 cm length of tungsten light bulb filament wire of diameter 0.090 mm. The resistivity of tungsten is shown in Table 2.

SOLUTION

Diameter (d) = 0.090 mm = 0.090×10^{-3} m

Radius (r) = 0.045×10^{-3} m

Length (L) = 4.0 cm = 4.0×10^{-2} m

Area (A) = $\pi r^2 = 3.14 \times (0.045 \times 10^{-3})^2 = 6.36 \times 10^{-9}\,\text{m}^2$

$$R = \frac{\rho L}{A} = \frac{5.6 \times 10^{-8} \times 4.0 \times 10^{-2}}{6.36 \times 10^{-9}} = 0.35\ \Omega$$

Resistors in practice

resistor
a device that reduces the flow of charge (current) in a circuit

Resistors are simple devices used to control the flow of electric current as well as to divide up a voltage into several smaller values. Resistors are generally of two types: fixed and variable. They differ considerably in physical size due to the total electrical power they are required to handle.

MANDATORY PRACTICAL
8.1 Finding resistance of an ohmic resistor
Go to page 480 »

Fixed resistors

Fixed resistors are usually made of some form of carbon mixture. The simplest type of resistor is the carbon composition resistor, which is made of finely divided graphite carbon mixed with a powdered insulating medium, such as crushed clay, in a defined proportion.

Study tip

Information about colour coding of resistors can be found on your obook assess.

Variable resistors

Quite often, long lengths of resistive wire are wound on special ceramic 'formers'. In conjunction with a sliding contact, this produces a 'rheostat' – a device whose resistance can be varied.

This type of device is used to control voltages in electric circuits and to act in conjunction with electric motors and dimmer switches. The common volume control knobs on radio, television and stereo equipment are always simple variable resistors.

FIGURE 2 A 5 Ω rheostat as used in school

CHECK YOUR LEARNING 8.1

Describe and explain

1 **Define** resistance.

2 **Explain** how length, cross-sectional area and material can affect resistance.

3 **Calculate** the cross-sectional area of a 50 cm length of nichrome wire of diameter 0.43 mm. Give your answer in square metres (m^2).

4 **Calculate** the resistance of a 1.50 m length of nichrome wire of diameter 0.015 mm. Refer to Table 2 for the resistivity of nichrome.

5 Students find a 30 cm length of nichrome wire that has a resistance of 8.5 Ω. **Calculate** the diameter.

Apply, analyse and interpret

6 Students want to use a piece of nichrome wire to make a 10.0 Ω heating element for an experiment. They have wire of diameter 0.376 mm. **Determine** what length they should use.

Investigate, evaluate and communicate

7 a **Determine** the resistivity of a piece of wire of length 20.0 m that has a diameter of 0.58 mm and a resistance of 1.13 Ω at 20°C by identifying it in Table 2.

b **Calculate** how much time it would it take to heat a cup of water (250 mL) from 20°C to boiling point if this wire (as mentioned above) was made into a coil and connected to a 12.0 V laboratory power supply.

c **Explore** any assumptions you have made about the heating of the water.

d **Assess** the effect on their experiment if students noticed that some of the loops in the coil were touching each other.

8 **Predict** the shape of a graph of resistance (vertical axis) vs diameter (horizontal axis) for three 1.0 m lengths of nichrome wire of different diameters.

Check your obook assess for these additional resources and more:

» Student book questions
Check your learning 8.1

» Mandatory practical
8.1 Finding resistance of an ohmic resistor

» Video
Resistance vs length

» Video
Thickness of wire with Vernier

8.2 Ohm's law

KEY IDEAS

In this section, you will learn about:

- how to solve problems using Ohm's law
- the difference between ohmic and non-ohmic resistors.

In 1825 and 1826, Ohm set up simple electric circuits containing a length of resistance wire as shown in Figure 1. He varied the voltage and noted the current through an ammeter (although he used slightly different terms at the time).

Ohm found that the current through the conductor was proportional to voltage across it, provided he kept everything else the same (length, area and temperature).

$$I \propto V$$

After Ohm published his work, other scientists expanded on his findings and defined the ratio of V to I (which is a constant) as the electrical resistance, R:

$$I = \frac{V}{R}$$

This relationship between voltage, current and resistance can be summarised as **Ohm's law**: Electric current is proportional to voltage and inversely proportional to resistance.

Ohm's law
electric current is proportional to voltage and inversely proportional to resistance

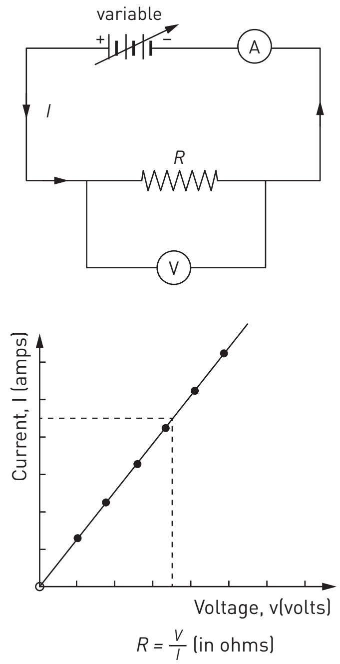


FIGURE 1 Ohm's law circuit

WORKED EXAMPLE 8.2

Determine the:

a resistance of a car horn if 1.50 A flows when 12.0 V is applied to it

b voltage across the same car horn when 250 mA is flowing.

SOLUTION

a Rearranging Ohm's law $I = \frac{V}{R}$ to $R = \frac{V}{I}$ and substituting known values gives:

$R = \frac{12.0}{1.5} = 8.0\ \Omega$

b $R = \frac{V}{I}$

$V = IR = 250 \times 10^{-3} \times 8.0 = 2.0\ \text{V}$

Ohmic and non-ohmic devices

If an electrical component follows Ohm's law, we say it is 'ohmic'. If it doesn't follow Ohm's law, we say it is 'non-ohmic'.

Ohmic devices

A good example of something ohmic is nichrome wire (Figure 2).

If a current through a 17.0 cm length of nichrome wire of diameter 0.274 mm was measured as the voltage increases, the results would be similar to those in Table 1.

TABLE 1 Voltage and current through nichrome wire

Voltage (V)	0.0	1.0	2.0	3.0	4.0	5.0
Current (A)	0.0	1.2	2.4	3.6	4.8	6.0

When the results are plotted, a graph similar to Figure 3 would be produced.

FIGURE 2 Nichrome wire is considered ohmic.

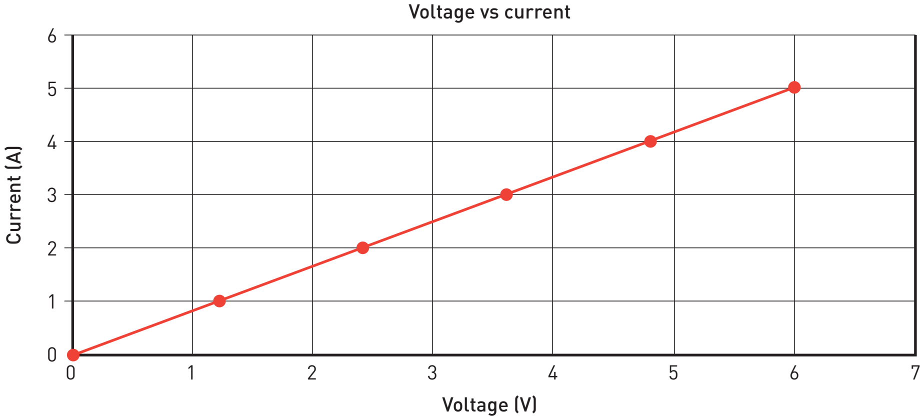


FIGURE 3 Graph of voltage (horizontal axis) vs current (vertical axis) for a piece of nichrome wire

Study tip

A worked example demonstrating the gradient changing when different resistors are used can be found on your obook assess.

Devices that have a directly proportional relationship for I vs V are said to be **ohmic devices**. A directly proportional graph is one that is linear and also passes through the origin (0, 0). The nichrome wire in the graphs mentioned so far is ohmic.

ohmic devices those that follow Ohm's law

Comparison of ohmic resistors

When different resistors are used, we would still observe straight lines on a voltage–current graph but the gradient changes. If 1.0 m of the nichrome wire and also a 2.0 m length of the same wire was used in a similar experiment to before, the graph of results would look like Figure 4. Both wires show a linear relationship, so they are both ohmic as expected. However, the 1.0 m length of wire has a resistance of 5 Ω, whereas the 2.0 m length has a resistance of 10 Ω. The gradient equals the reciprocal of the resistance.

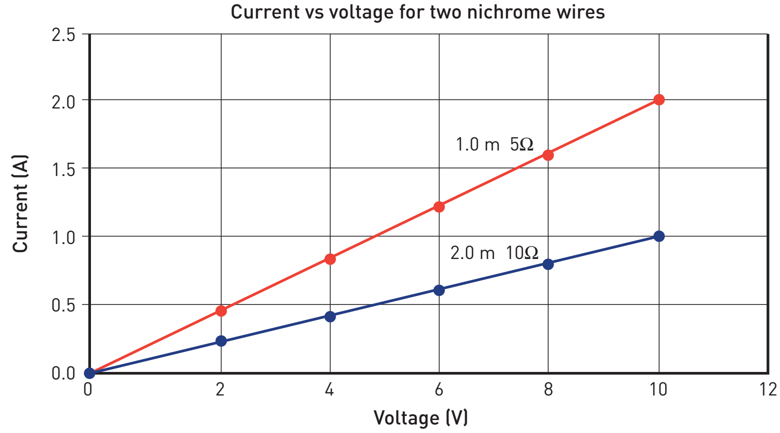


FIGURE 4 Voltage–current characteristics for a 1 m and 2 m length of nichrome wire. When voltage is plotted on the horizontal axis, the steeper the line, the smaller the resistance.

Non-ohmic devices

The many substances for which Ohm's law holds are called **ohmic**. These include good conductors such as copper, aluminium and nichrome, and even a non-conductor like silicon.

non-ohmic
not following Ohm's law

They all obey Ohm's law over a certain range of voltages. But if the voltage gets high enough, there will be departures from Ohm's law in **all** cases. They become **non-ohmic**.

FIGURE 5 Copper is an example of an ohmic substance.

Effect of temperature

The essence of Ohm's law is that the *V*–*I* graph is linear, but it is not a fair test of the law if the object heats up as well. The temperature and physical factors must remain constant to be able to apply Ohm's law. The resistance will change if the object heats up (like it does in a light bulb), but this is not a fair test of Ohm's law.

If the temperature of a wire gets too high, ohmic devices can become non-ohmic. A light bulb is considered a non-ohmic device for this reason. It obeys Ohm's law for low voltages when it is cool, but at higher voltages it gets hotter and so the resistance gets greater. As the voltage increases, the electrons carry more energy. When they collide with metal atoms in the conductor, they transfer more energy. This makes the atoms vibrate a lot more and increases the resistance. Hence, the voltage–current graph does not follow a straight line.

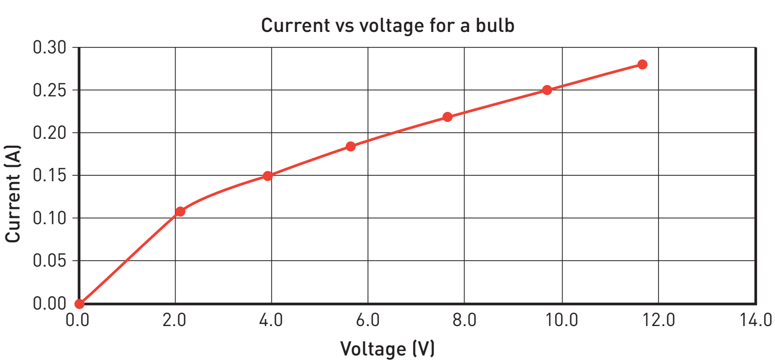
This effect can be seen on the graphs in Figure 6 for an actual experiment measuring the current/voltage characteristics of a light bulb. As the light bulb heats, the resistance gets bigger and the graph is no longer linear but is instead a curve. For this reason, the light bulb is called non-ohmic. If you could stop the light bulb from heating up (using ice perhaps), its resistance would remain constant and the graph would be linear and hence ohmic.

There is no single resistance of a light bulb as shown in the graphs. Its resistance changes at higher voltages and currents. However, you can calculate its instantaneous resistance at any given voltage. For example, the instantaneous resistance at 4.00 V, where the current is 0.150 A, is:

$$R = \frac{V}{I} = \frac{4.00}{0.150} = 26.7\ \Omega$$

At 8.00 V where the current is 0.225 A, the resistance is:

$$R = \frac{V}{I} = \frac{8.00}{0.225} = 35.5\ \Omega$$



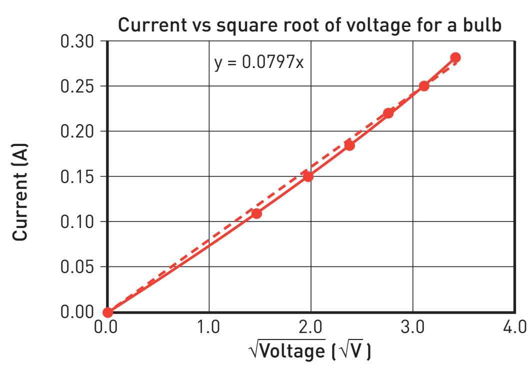


FIGURE 6 Graphs showing the current vs voltage curves using student data for a 12 V light bulb. The relationship appears to be $y \propto \sqrt{x}$.

True non-ohmic devices

The best examples of true non-ohmic conductors are modern semiconductor devices such as transistors, diodes and thermistors. These are designed to be non-ohmic.

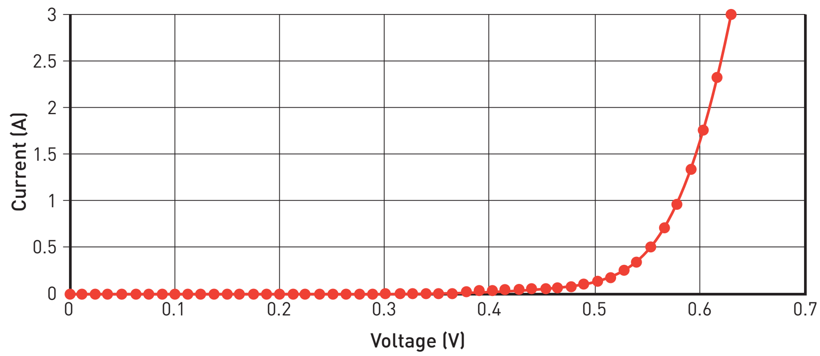


FIGURE 7 The characteristic *I–V* curve for a silicon semiconductor diode. At about 0.55 V, the current increases dramatically without heating up. It is like a voltage-controlled switch that turns on at 0.55 V.

Study tip

Non-ohmic devices rarely have a straightforward mathematical relationship between *V* and *I*. However, in the case of a light bulb we discussed, the proposed relationship $y \propto \sqrt{x}$ can be confirmed by the linearised graph in which *y* (current) is plotted against the $\sqrt{x}$ (square root of voltage). As shown in Figure 6(a), a linear relationship is found.

CHECK YOUR LEARNING 8.2

Describe and explain

1 **Explain** Ohm's law in your own words.

2 **Describe** the difference between an ohmic and a non-ohmic device.

3 **Calculate** the current flowing through the bulb of a 4.5 V torch when its resistance is 4.60 Ω.

4 **Calculate** the resistance of a mobile phone that has a 1.35 V battery and through which 0.150 mA flows.

Apply, analyse and interpret

5 **Determine** the resistance of a portable amplifier when 1.50 A flows through it as the battery applies 12.0 V to the circuit.

6 **Determine** the voltage needed to operate a laser pointer that has a resistance of 140 Ω, given that 20.0 mA passes through it.

7 **Deduce** the voltage drop in a headphone cord having 1.2 kΩ resistance and through which 10 mA is flowing.

8 A student set up the experimental apparatus as shown in Figure 8 and found results as tabulated in Table 2.

a **Determine** the value of the resistance at all points using $R = \frac{V}{I}$.

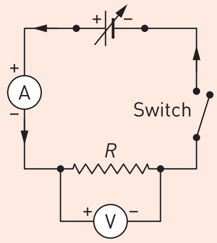


FIGURE 8 Experiment set-up

TABLE 2

Voltage (V)	0	2	4	6	8	10	12
Current (A)	0.0	0.013	0.025	0.04	0.05	0.06	0.08

b **Sketch** a voltage (horizontal axis) versus current (vertical axis) graph and calculate the gradient. **Describe** what you find.

c **Explain** if the resistor is 'ohmic' in its characteristics.

Investigate, evaluate and communicate

9 Students connected a resistor to a laboratory power supply and measured the voltage across the resistor and the current passing through it. The meter readings are shown in Figure 9.

FIGURE 9 Voltage and current readings

a **Determine** the 'best estimate' readings on the meters and estimate scale reading uncertainties.

b **Calculate** the experimental value of the resistance, including absolute and percentage uncertainty.

c **Calculate** the absolute and percentage error in the experimental value of resistance if the accepted value of the resistance is 220 Ω.

d **Propose** whether the resistor is within the tolerance range of ± 10%.

e **Modify** the following conclusion to make it more acceptable: 'Because $V = IR$, the resistor must be ohmic'.

10 Table 3 shows experimental data from a light bulb.

a **Construct** an appropriate graph. (Place voltage on the horizontal axis.)

b **Propose** a relationship and generate a linearised graph. Sketch a line of best fit (trendline) and express the relationship in the form of an equation. Generate and display the R^2 value. Evaluate the fit of the data to the line by considering the closeness of the R^2 value to 1.00.

c **Comment**, with reference to the data, on whether the light bulb is ohmic or non-ohmic.

TABLE 3

	Current (A)		Voltage (V)	
Power supply	Trial 1	Trial 2	Trial 1	Trial 2
0 V	0.0	0.0	0.0	0.0
2 V	0.11	0.11	2.14	2.13
4 V	0.15	0.15	3.87	3.88
6 V	0.19	0.18	5.63	5.60
8 V	0.22	0.22	7.69	7.56
10 V	0.25	0.25	9.67	9.69

Check your obook assess for these additional resources and more:

» **Student book questions**
Check your learning 8.2

» **Suggested practical**
8.2 Ohmic and non-ohmic resources

» **Increase your knowledge**
Worked example demonstrating gradient change with different resistors

» **Weblink**
Ohm's law

8.3 Resistors in series and parallel

KEY IDEAS

In this section, you will learn about:

+ resistance in series and parallel.

If you look inside an electronic device, you'll see dozens of resistors in all sorts of odd combinations. Most circuits have more than one resistor. The simplest combinations of resistors are the series and parallel connections illustrated in Figures 1 and 2. The total resistance of a combination of resistors depends on both their individual values and how they are connected.

Resistors in series

Figure 1 shows three resistors connected in series so that any charge flowing from A to B must pass through each in turn. This effect simply adds the individual resistances to create a total of all three. It is the same as increasing the effective length of a single resistor.

Therefore:

$$R_t = R_1 + R_2 + \cdots + R_n$$

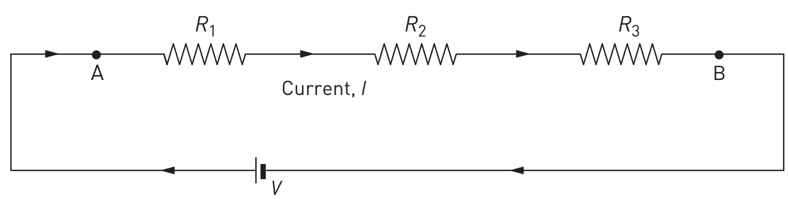


FIGURE 1 Resistors in series

As the charge passes through each resistor, the charge loses some of its energy to heat. If the three resistances are all the same value, the potential difference across each resistor is the same. The total voltage is divided up between the series resistors. This will be dealt with in a later section.

Summary

To summarise resistors in series, we can say:

1 Series resistances add: $R_t = R_1 + R_2 + \cdots + R_n$

2 The same current flows through each resistor in series.

3 Individual resistors in series do not receive the total source voltage, but instead divide it.

WORKED EXAMPLE 8.3A

What is the total resistance of three resistors (10 Ω, 33 Ω and 100 Ω) connected in series?

SOLUTION

$R_t = R_1 + R_2 + R_3$

$= 10 + 33 + 100$

$= 143\ \Omega$

Resistors in parallel

Figure 2 shows three resistors connected in parallel, similar to the rungs of a ladder. Current flowing from A to B in this situation has three paths it could take. In a sense, the total cross-sectional area of the conductor for current (I) is being increased, and thus the total resistance is reduced.

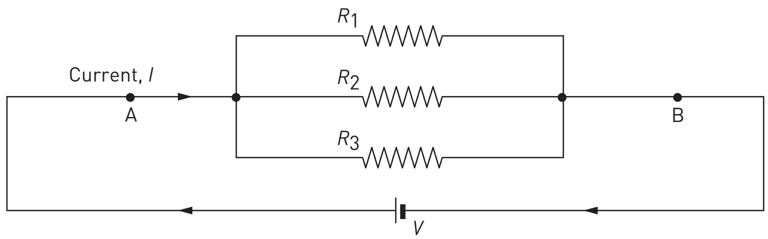


FIGURE 2 Resistors in parallel

If the three resistances are equal, then $\frac{1}{3}$ of the current goes through each. However, the potential difference between A and B (ΔV_{AB}) is the same for each ($\Delta V_{R1} = \Delta V_{R2} = \Delta V_{R3}$). Even if the three resistances are different, the potential difference (voltage) across each one of them is still the same.

To work out the overall resistance, we must add of the reciprocals of each resistance to give a relationship expressed as:

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots + \frac{1}{R_n}$$

Summary

Parallel resistance can be summarised in the following way:

1. Parallel resistance is found from $\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots + \frac{1}{R_n}$ and it is smaller than any individual resistance in the combination.
2. Each resistor in parallel has the same full voltage of the source applied to it.
3. Parallel resistors do not each receive the total current. Instead, they divide it.

FIGURE 3 Is it more efficient to turn off a light when you leave the room?

CHALLENGE 8.3

Lights on or off

Is it more efficient to turn off a light when you leave the room and then turn it on again when you re-enter, or just leave the light on the whole time? How would you test this?

WORKED EXAMPLE 8.3B

Three resistors (10 Ω, 33 Ω and 100 Ω) are connected in parallel. Calculate the total resistance of the combination.

SOLUTION

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} = \frac{1}{10} + \frac{1}{33} + \frac{1}{100} = 0.140$$

$$\frac{1}{R_t} = 0.140$$

$$R_t = \frac{1}{0.140} = 7.1\ \Omega$$

WORKED EXAMPLE 8.3C

Calculate the total resistance of a pair of 25 Ω resistors connected in parallel to a battery whose EMF is 12 V. Deduce the current, measured by a DC ammeter, that will flow from the battery.

SOLUTION

Calculate the total effective resistance:

$$\frac{1}{R_t} = \frac{1}{25} + \frac{1}{25} = \frac{2}{25}$$

$R_t = 12.5\ \Omega$

$= 13\ \Omega$

Use $V = I \times R_t$ to find current as measured by the ammeter:

$12 = I \times 12.5$

$$I = \frac{12}{12.5} = 0.96\text{ A}$$

CHECK YOUR LEARNING 8.3

Describe and explain

1 **Explain** whether resistors in series can ever have a combined resistance smaller than any one of the resistors in the combination.

2 Three resistors of resistances 2 Ω, 4 Ω and 6 Ω are connected in parallel.

a **Calculate** the equivalent resistance.

b **Calculate** the total resistance when the three resistors are connected in series.

Apply, analyse and explain

3 Two equal resistors are connected in parallel and give a combined resistance of 5 Ω. **Determine** the resistance of each of the two resistances.

4 A 100 Ω resistor is connected in parallel with an unknown resistor to give a combined resistance of 66.7 Ω. **Determine** the value of the unknown resistor.

Investigate, evaluate and communicate

5 **Propose** whether the combined resistance of two resistors in parallel ever be greater than either of the two resistances.

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8.3 Lights on or off

» Increase your knowledge
Resistance and temperature

» Weblink
Resistors

CHAPTER 8

Review

Summary

8.1
- Resistance is the opposition to the flow of electric current through a conductor and is measured in units called ohms. It is defined as the ratio $\frac{V}{I}$.

8.2
- Ohm's law states that $I \propto V$ when all other factors are held constant.
- Ohm's law can be written as: $I = \frac{V}{R}$
- The resistance of an ohmic conductor is directly proportional to its length and inversely proportional to its cross-sectional area.
- Ohmic resistors obey Ohm's law; non-ohmic resistors do not.

8.3
- Resistors may be connected in series or parallel configurations: for resistors in series, $R_t = R_1 + R_2 + \cdots + R_n$ and for resistors in parallel, $\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots + \frac{1}{R_n}$.

Key terms

- electrical resistance
- non-ohmic device
- Ohm's law
- ohmic device
- resistivity
- resistor

Key formulas

Resistance	$R = \frac{V}{I}$
Overall resistance (resistors in series)	$R_t = R_1 + R_2 + \cdots + R_n$
Overall resistance (resistors in parallel)	$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots + \frac{1}{R_n}$
Resistivity in a wire	Resistivity $R = \frac{\rho L}{A}$

Revision questions

The relative difficulty of these questions is indicated by the number of stars beside each question number: ★ = low; ★★ = medium; ★★★ = high.

Multiple-choice

1 The resistance of a torch bulb drawing 2.0 A current at 12.0 V is:

A 1.7 Ω
C 14 Ω
B 6 Ω
D 24 Ω

2 The current in a wire:

A depends only on the potential difference applied.
B depends only on the resistance of the wire.
C depends on both resistance and potential difference.
D does not depend on resistance and potential difference.

3 Ohm's law relates potential difference with which of the following?

A power
C current
B energy
D time

4 Which one of the following is an ohmic resistor?

A diode
C nichrome
B silicon
D diamond

5 The resistivity of a wire depends on which of the following?

A length
B material
C cross-sectional area
D length, material and cross-sectional area

Short answer

Describe and explain

★ 6 **Define** resistance, and state its unit and unit symbol.

★ 7 **Recall** a high-resistance and a low-resistance substance and explain at an atomic level why they each have this resistance.

★ 8 **Calculate** the voltage across a torch bulb of resistance 24 Ω when 250 mA is flowing.

★ 9 Three resistors are connected in parallel. They have resistances of 3 Ω, 6 Ω and 9 Ω. **Calculate** their combined (total) resistance.

★★ 10 **Explain** what factors affect the resistance of a conductor.

★★ 11 **Recall** Ohm's law and explain what part resistance plays in this relationship.

★★ 12 **Explain** how you would recognise the characteristics of ohmic and non-ohmic substances.

★★ 13 **Describe** how you would determine the resistance of a substance from a *V* vs *I* graph.

★★ 14 **Explain** how you would recognise an 'anomaly' in the data for a voltage vs current experiment.

★★ 15 **Explain** whether this claim is true: 'When you compare the experimental resistance of a ceramic resistor with its stated value, you can determine the absolute error of your measurement'.

★★ 16 **Calculate** the resistance of a 50 m length of silver wire of cross-sectional area 0.50 mm^2 at 20°C. (Refer to p. 232 for resistivity of silver.)

★★ 17 A piece of metal wire of length 20.0 m has a diameter of 0.58 mm and a resistance of 1.13 Ω at 20°C. Using the table of resistivities (p. 232), **identify** which metal it is.

★★ 18 Two 10 Ω resistors are connected in parallel. **Identify** if the following are the same or not the same in each resistor:

a current
c potential difference
b resistance
d power

★★★ 19 You have a 100.0 m length of resistance wire of uniform cross-sectional area 0.1 mm^2 ($\rho = 50 \times 10^{-8}$ Ω m). The wire is now drawn out (stretched) to three times its original length.

a **Demonstrate** that the original resistance of the wire was 500 Ω.
b **Calculate** how many times greater the new resistance of the wire is.

Apply, analyse and interpret

★ 20 **Determine** the resistance of a car headlight if 1.50 A flows when 12.0 V is applied to it.

★★ 21 A 10 Ω and a 20 Ω resistor are connected in parallel. **Deduce** if the following are the same or not the same in each resistor:

a current
c potential difference
b resistance
d power

★★ **22** Two 10 Ω resistors are connected in series. **Deduce** if the following are the same or not the same in each resistor:

- **a** current
- **b** resistance
- **c** potential difference
- **d** power

★★ **23** A10 Ω and a 20 Ω resistor are connected in series. **Deduce** if the following are the same or not the same in each resistor:

- **a** current
- **b** resistance
- **c** potential difference
- **d** power

★★ **24** A pigeon stands on a 100 kV overhead wire that carries 50 A. If the line resistance is $2.0 \times 10^{-4}\ \Omega\ m^{-1}$ (ohms per metre), **calculate** the voltage across the bird if its feet are 3.0 cm apart. **Deduce** the likelihood of the pigeon being electrocuted.

★★ **25** Conducting metal A has a resistance of 0.36 Ω at 25°C. **Determine** the resistance of conducting metal B compared to conducting metal A under the following conditions:

- **a** B is three times longer than A.
- **b** B is only half the cross-sectional area of A.
- **c** B has just been taken from an oven operating at 350°C.

★★ **26** **Calculate** the length of tungsten wire that has the same resistance as 1.5 m of nichrome wire of the same cross-sectional area.

★★ **27** An aluminium cylinder of length 10 cm and diameter 2 cm is being used for an experiment.

- **a** **Calculate** its resistance.
- **b** **Determine** the resistance of a similar-sized carbon rod.

★★ **28** The following data was collected from an Ohm's law experiment in which the voltage across a circuit device was changed and the current passing through it measured.

TABLE 1

Voltage (V)	0.0	1.5	3.0	4.5	6.0	7.5
Current (A)	0	0.1	0.2	0.3	0.4	0.5

- **a** **Sketch** this data on a suitable graph.
- **b** Using your graph:
  - **i** **determine** if the device is ohmic
  - **ii** **calculate** the resistance by graphical means
  - **iii** **deduce** the voltage at 0.6 A by extrapolation
  - **iv** **deduce** the current at 2.0 V by interpolation.

★★★ **29** A piece of nichrome wire is required for a heating experiment. It must have a 2.2 Ω resistance and be 10.0 cm long. **Determine** what diameter wire (in mm) you would use.

★★★ **30** **Determine** the diameter of a roll of nichrome wire that is labelled $4.6\ \Omega\ m^{-1}$.

★★★ **31** Two 1.0 m lengths of silver wire and aluminium wire, each of diameter 0.8 mm, are connected in parallel. **Deduce** their effective resistance.

Investigate, evaluate and communicate

★★ **32** **Assess** the claim that 'all metals obey Ohm's law'. Justify your conclusion with evidence as to the veracity of the claim.

★★★ **33** A 100 Ω ± 10% fixed resistor was used in an Ohm's law experiment where pairs of *V* vs *I* data were collected. The data is displayed in Table 2.

TABLE 2

Voltage (V)	0.0	1.8	3.4	4.9	6.7	8.7	10.5	11.5
Current (A)	0.000	0.022	0.038	0.062	0.082	0.100	0.125	0.132

- **a** **Construct** a graph of the data, with V on the horizontal axis.
- **b** **Assess** whether the resistor is ohmic.
- **c** **Construct** a trendline, and, if using Excel, show the equation and display the R^2 value.
- **d** **Determine** the relationship between V and I.
- **e** **Discuss** the meaning of the gradient 'm' in the equation $y = mx$. **Express** a view on the meaning of the 'goodness of fit' R^2 value and what it tells you about the data.
- **f** **Determine** the experimental value of the resistance.
- **g** **Determine** the absolute and percentage errors. **Assess** whether the experimental value is within the ±10% tolerance range allowed by the manufacturer.

★★★**34** A student set up a circuit to collect *V* vs *I* data for an experiment to assess a device as ohmic or non-ohmic. The results are tabulated in Table 3.

TABLE 3

Voltage (V)	2.0	4.0	6.0	8.0	10.0	12.0
Current (A)	0.013	0.025	0.040	0.050	0.060	0.080

- **a** **Determine** the value of the resistance at all points.
- **b** **Construct** a graph of voltage (horizontal axis) versus current (vertical axis) graph.
- **c** **Deduce,** with evidence, whether the resistor is ohmic or non-ohmic.

★★★ **35** Students set up an Ohm's law circuit to measure the voltage and currency characteristics of a piece of SWG 30 nichrome wire of diameter 0.315 mm. The voltage across the ends of a 124.0 cm length of wire was increased and the following currents (in mA) were recorded:

TABLE 4

Voltage (V)	2.0	4.0	6.0	8.0
Current (A)	125	245	380	495

- **a** **Determine** the resistance of the wire.
- **b** **Calculate** the theoretical ('accepted') resistance using the resistivity value of nichrome wire as ρ (nichrome) = $100 \times 10^{-8} \Omega$m.
- **c** **Assess** the absolute error and relative error by comparing your experimental 'observed' resistance (O) to the accepted value.

★★★**36** The following data was obtained from a student experiment into the voltage/current characteristics of a circuit device

TABLE 5

Voltage (V)	0.00	2.13	3.86	5.65	7.65	9.67	11.66
Current (A)	0.00	0.12	0.16	0.19	0.22	0.25	0.27

- **a** **Assess** whether the device is ohmic and **construct** a linearised graph if the relationship is not ohmic.
- **b** **Discuss** the relationship.

★★★ **37** In an Ohm's law experiment students collected the pairs of data shown in Table 6.

TABLE 6

V_{AB}	±0.05 V	0.50	1.00	1.50	2.00	2.50	3.00	3.50
I (A)	±0.05 A	0.10	0.21	0.30	0.40	0.48	0.61	0.70

- **a** **Construct** a graph of the data and include fixed error bars for both V_{AB} (horizontal axis) and I (vertical axis).
- **b** **Construct** a line of best fit through the data points but ensuring the line is within the error bars.
- **c** **Determine** the gradient of the linear trendline, and the gradient of the maximum and minimum line of best fit.
- **d** **Assess** the data.

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CHAPTER 9

Circuit analysis and design

Why is it that some birds can sit on 11 000 V overhead wires without a problem, whereas bigger animals such as bats get electrocuted? If a larger animal touches more than one wire, the charge will pass through its body. Birds perched on a single wire are at a potential of 11 000 V, but the charge has nowhere to go. The ground (0 V) is many metres below them. A circuit must be completed before charge flows.

OBJECTIVES

→ Recall that electric charge is conserved at all points in an electrical circuit and recognise this as Kirchhoff's current law.
→ Explain that the energy inputs in a circuit equal the sum of energy output from loads in the circuit and recognise this as Kirchhoff's voltage law.
→ Recognise series and parallel connections of components in electrical circuits.
→ Recall resistor, voltmeter, ammeter, cell, battery, switch and bulb circuit diagram symbols.
→ Solve problems involving electrical potential difference, electric current, resistance and power in series and parallel circuits.
→ Define power dissipation over resistors in a circuit.
→ Design simple series, parallel and series/parallel circuits.

Source: *Physics 2019 v1.2 General Senior Syllabus Queensland Curriculum & Assessment Authority*

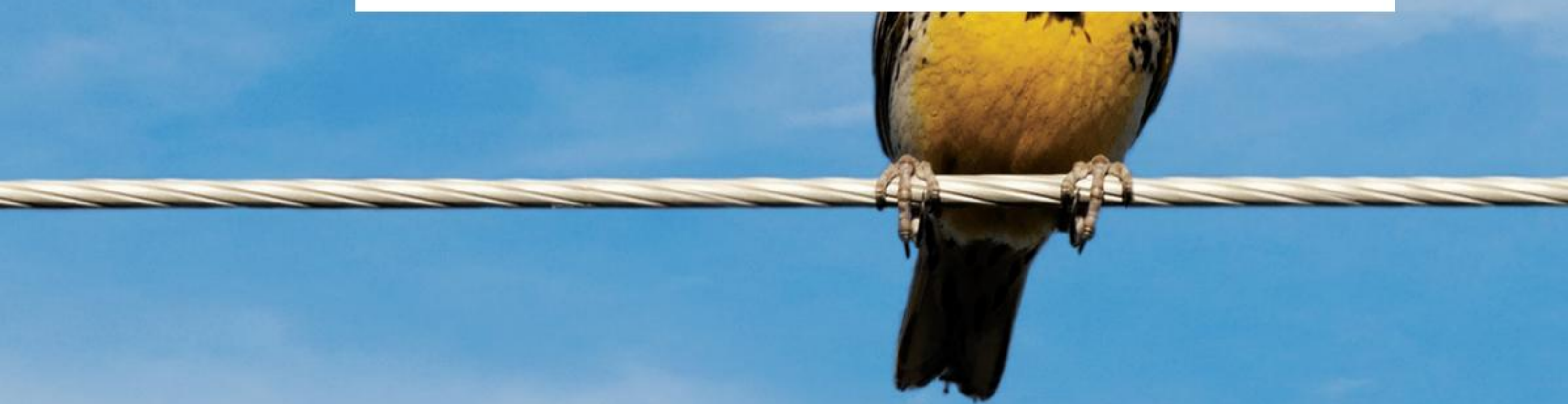


FIGURE 1 Birds perched on a wire are at a potential of 11 000 V but feel no effects. As long as they keep their feet together they are safe.

MAKES YOU WONDER

In this chapter we will be examining some aspects of electric circuits that will help to answer questions such as:

→ How does a volume control on a loudspeaker work?
→ Why do some bulbs get hot and others stay cool even when they give out the same light?
→ At boat ramps why are there signs that say, 'Sailors lower your masts'?

PRACTICALS

SUGGESTED PRACTICAL	**9.1** Investigating series and parallel circuits
SUGGESTED PRACTICAL	**9.2** Circuits for real life purposes-using a fuse for protection

9.1 Kirchhoff's circuit laws

KEY IDEAS

In this section, you will learn about:

- Kirchhoff's current law
- Kirchhoff's voltage law.

FIGURE 1 German physicist Gustav Robert Kirchhoff

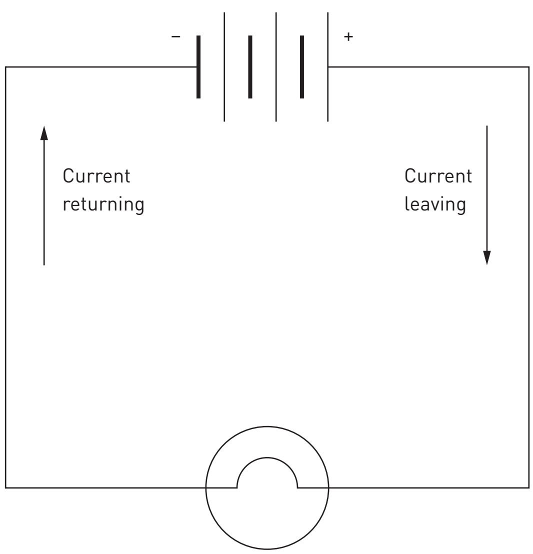


FIGURE 2 Current is the flow of charge in a circuit.

The word circuit comes from the Latin *circumire*, meaning 'to go around' – hence the words circle, circumference and circus (horses and chariots go around the ring). Here we'll be talking about conventional positive charge going around a wire.

Charge leaving a battery is the same as the charge returning to it. If there is nothing else hooked up to the battery, then the charge just goes around the circuit. Also, the current leaving a battery is the same as the current returning – otherwise the charges would pile up somewhere or there would be gaps if some of it raced ahead. It is not like cars on the road where the gaps between the cars can change. The electrons all carry the same charge and keep a uniform distance.

Ohm's law ($I \propto V$) is one of the most important laws in physics. In chapter 8, Ohm's law told us how voltage and current were related through a resistor. However, this law didn't cover complicated situations such as when three wires come in to a circuit and meet but only two come out.

The next two circuit laws were formulated by German physicist Gustav Robert Kirchhoff (1824–1887) while studying electrical networks.

SUGGESTED PRACTICAL

9.1 Investigating series and parallel circuits
Go to your obook assess »

Kirchhoff's current law

The first of these laws is based on the law of conservation of electric charge and applies to junction points in a circuit – points where three or more wires join together. These points are sometimes called 'nodes' (Latin for 'knot'). The law is usually referred to as **Kirchhoff's current law (KCL)** and is represented in Figure 3.

Kirchhoff's curren`t law (KCL)
at any node in an electrical circuit, electric charge is conserved such that the sum of the electric currents flowing into a node is equal to the sum of electric currents flowing out of that node

$$I_t = I_1 + I_2 + \ldots + I_n$$

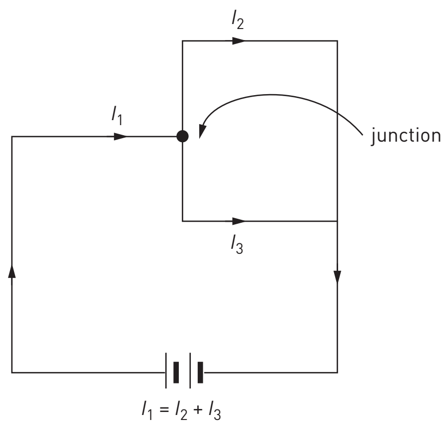


FIGURE 3 Kirchhoff's current law

WORKED EXAMPLE 9.1A

Calculate the value of *I* for the junctions in the following circuits.

a

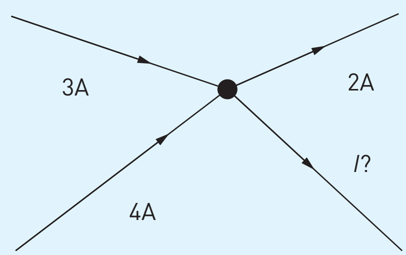


FIGURE 4 Calculate the value of *I*

b

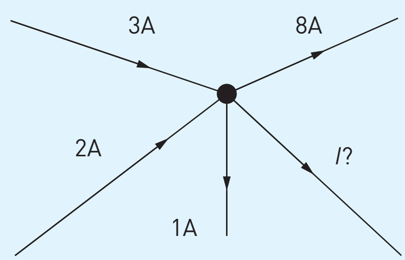


FIGURE 5 Calculate the value of *I*

SOLUTION

a $I_{in} = 3 + 4 = 7$ A

$I_{out} = 2 + I$

By KCL:

$I_{in} = I_{out}$

$7 = 2 + I$

$I = 7 - 2 = 5$ A out

b $I_{in} = 3 + 2 + I$

$I_{out} = 8 + 1 = 9$ A

By KCL:

$I_{in} = I_{out}$

$5 + I = 9$

$I = 9 - 5 = 4$ A in

Kirchhoff's voltage law

Kirchhoff's voltage law (KVL) the energy inputs in a circuit equal the sum of energy output from loads in the circuit such that the directed sum of the electric potential differences around any closed network is zero

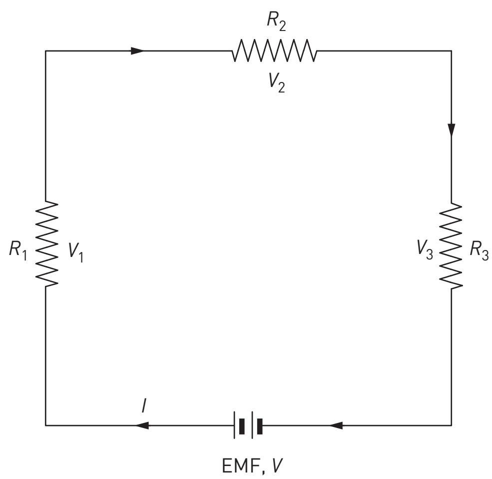
The second law is called **Kirchhoff's voltage law (KVL)** and is based on the law of conservation of energy as applied to complete closed-circuit paths or loops.

Consider the circuits in Figure 6. The diagram on the left shows a simple circuit with a battery as the source of EMF (V), and three resistors R_1, R_2 and R_3 with corresponding potential differences V_1, V_2 and V_3. The diagram beside it gives specific values for potential difference so that Kirchhoff's voltage law can observed in action.

The potential gain at the source of EMF (V) is equal in magnitude to the sum of potential losses around the circuit through the three resistors R_1, R_2 and R_3: thus $V = V_1 + V_2 + V_3$.

Kirchhoff's voltage law: the energy inputs in a circuit equal the sum of energy output from loads in the circuit such that the directed sum of the electric potential differences around any closed network is zero.

$$V_t = V_1 + V_2 + \dots + V_n$$



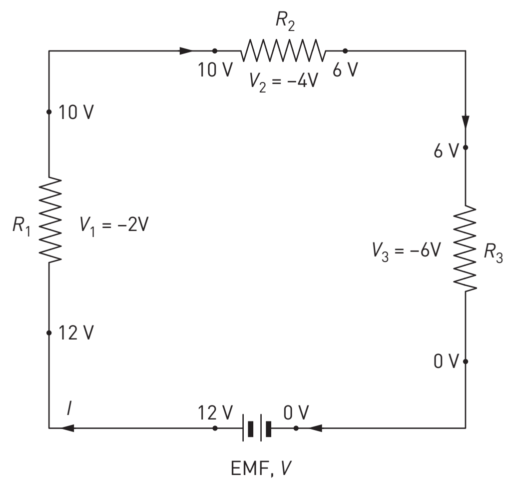


FIGURE 6 Kirchhoff's voltage law

CHALLENGE 9.1

Operating a lamp

a Incandescent light bulbs have a life proportional to $\frac{1}{V^{14}}$ seconds (where V is the applied voltage). Hence, if you run a 240 V bulb at 80% of its rated voltage you will increase its lifetime. Propose by how many times its life will be increased. We think 23 times; but how did we get that?

b Design and draw the diagram for a two-way model circuit that will operate a lamp from two different locations in a house, say, from upstairs or downstairs. The switches are shown in Figure 7.

FIGURE 7 Switches for a two-way model circuit

WORKED EXAMPLE 9.1B

For the circuit in Figure 8, calculate:

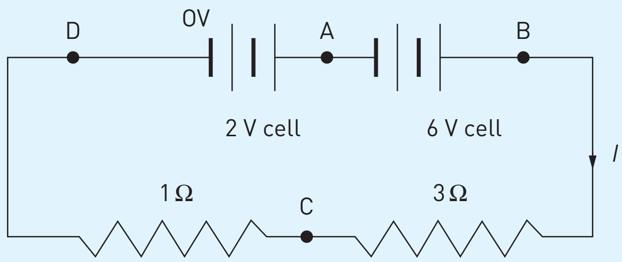


FIGURE 8 Circuit diagram

a V_A and V_B

b total resistance, R_t

c circuit current, I

d $\Delta V_{3\Omega}$ and $\Delta V_{1\Omega}$

e V_C.

SOLUTION

a $V_A = 0 + 2 = 2$ V

$V_B = 2 + 6 = 8$ V

(This is the total EMF of the two cells; call it V_t.)

b R_t(in series) $= 1 + 3 = 4\ \Omega$

c $I = \frac{V_T}{R_t} = \frac{8}{4} = 2$ A

d $\Delta V_{3\Omega} = I \times 3 = 2 \times 3 = 6$ V

$\Delta V_{1\Omega} = I \times 1 = 2 \times 1 = 2$ V

e $V_C = V_t - \Delta V_{3\Omega} = 8 - 6 = 2$ V

Cross-check to see if the p.d. across the 1 Ω resistor takes the voltage back to 0 V:

$V_C - 2 = 2 - 2 = 0$ V (which is what it should be back at the negative terminal of the cell).

Note: the voltage rise across the two cells (2 + 6 = 8 V) equals the voltage drops across the two resistors (6 + 2 = 8 V). This is Kirchhoff's voltage law in action.

Study tip

The word 'directed' means algebraic using ± terminology, so the potential differences are assigned + (for gains, such as the battery) and − for losses such as the resistors. When the ± signs are included, the algebraic sum is zero.

$V + V_1 + V_2 + V_3 = 0$

or $+12 + (-2) + (-4) + (-6) = 0$.

In using the KVL, either approach is suitable.

Circuit laws calculations

In the analysis of most DC circuits, the three laws – Ohm's law, KCL and KVL – are used in combination.

WORKED EXAMPLE 9.1C

Figure 9 shows a circuit containing a simple network of three resistors connected to a DC battery of 12 V. Use circuit laws to calculate the readings on:

a the ammeter A_1

b the ammeter A_2

c the voltmeter V.

SOLUTION

a Look at the circuit – if we can work out the total resistance, we can work out the total current. To work out the total resistance, we must find:

- the equivalent resistance of the parallel (||) pair of resistors between XY. Call this R_{XY}
- the total equivalent resistance (R_T) in the circuit
- the total current flowing from the battery, A_1.

For the parallel pair:

$$\frac{1}{R_{XY}} = \frac{1}{R_2} + \frac{1}{R_3}$$

$$\frac{1}{R_{XY}} = \frac{1}{10} + \frac{1}{10}$$

$$R_{XY} = 5\ \Omega$$

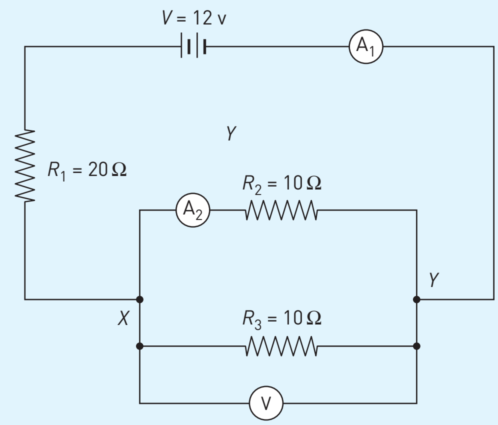


FIGURE 9 Three resistors connected to a 12 V DC battery

Note: the circuit could now be redrawn with only this single equivalent resistor. Thus, total circuit resistance:

$R_T = R_1 + R_{XY} = 20 + 5 = 25\ \Omega$

Total current flowing from battery:

$I_T = \frac{V}{R_T} = \frac{12}{25}$ = 0.48 A = 480 mA This is the reading on ammeter A_1.

b To calculate the current in meter A_2, we need to know:

- the voltage drop across the equivalent resistance XY, V_{XY}
- the current flowing through resistor R_2 measured by meter A_2.

Because of Kirchhoff's voltage law:

$$V = V_{XY} + I_T \times R_1$$

$$V_{XY} = V - (I_T \times R_1)$$

$$= 12 - (480 \times 10^{-3} \times 20)$$

$$= 2.4\ \text{V}$$

Notice that the sum of voltages around the circuit is 2.4 V + 9.6 V = 12 V. Thus, the current flowing through the resistor R_2 is given by:

$$V_{XY} = I_2 \times R_2$$

$$2.4 = I_2 \times 10$$

$$I_2 = 0.24\ \text{A} = 240\ \text{mA}$$

This is the reading on ammeter A_2.

c We have already calculated the voltage on the meter V in part (b).

The voltage on V is 2.4 V

CHECK YOUR LEARNING 9.1

Describe and explain

1 **Recall** Kirchhoff's current law and Kirchhoff's voltage law.

2 **Calculate** the current *I* in the following circuits:

a

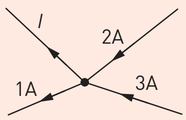


FIGURE 10 Calculate the value of *I*

b

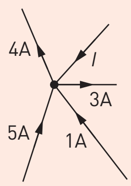


FIGURE 11 Calculate the value of *I*

3 For the circuit in Figure 12, **calculate:**

a the total resistance for the whole circuit

b currents I_1, I_2 and I_3

c the voltage at point X.

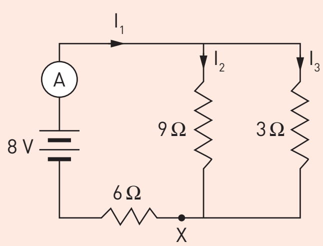


FIGURE 12 Circuit diagram

4 For the circuit in Figure 13, **calculate:**

a currents I_1, I_2 and I_3

b V_Y and V_Z.

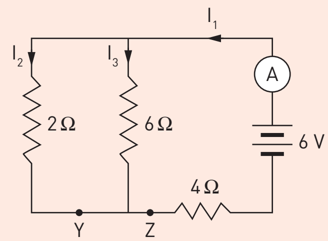


FIGURE 13 Circuit diagram

5 For the circuit in Figure 14, **calculate:**

a the value of resistor R

b the voltage at point P.

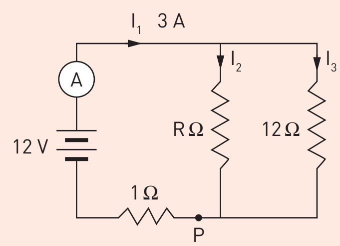


FIGURE 14 Circuit diagram

6 The circuit in Figure 15 has three resistors in series. **Calculate:**

a V_A and V_B

b the current, *I*

c V_C and V_D

d the p.d. across the 2 Ω resistor.

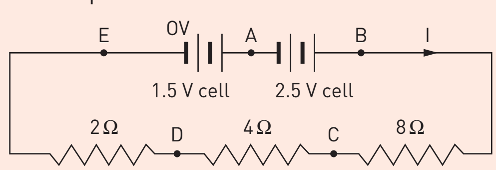


FIGURE 15 Three resistors in series

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» **Suggested practical**
9.1 Investigating series and parallel circuits

» **Challenge**
9.1 Operating a lamp worksheet

» **Weblink**
Kirchoff

9.2 Circuit analysis

KEY IDEAS

In this section, you will learn about:

+ circuit diagram symbols for resistor, voltmeter, ammeter, cell, battery, switch and bulb
+ solving problems involving electrical potential difference, electric current, resistance in series and parallel circuits.

We have already been using several common electric circuit symbols.

Circuit symbols

Electric circuit diagrams are the standard method of representing actual circuits in practice. Some standard electric symbols used are shown in Figure 1. Note that a rectangular style is used when drawing electric circuit diagrams for ease of reading the connections between various components. The actual working circuit may not follow this rectangular style, especially if forming part of a printed circuit board in a consumer electronic device such as a television set or computer.

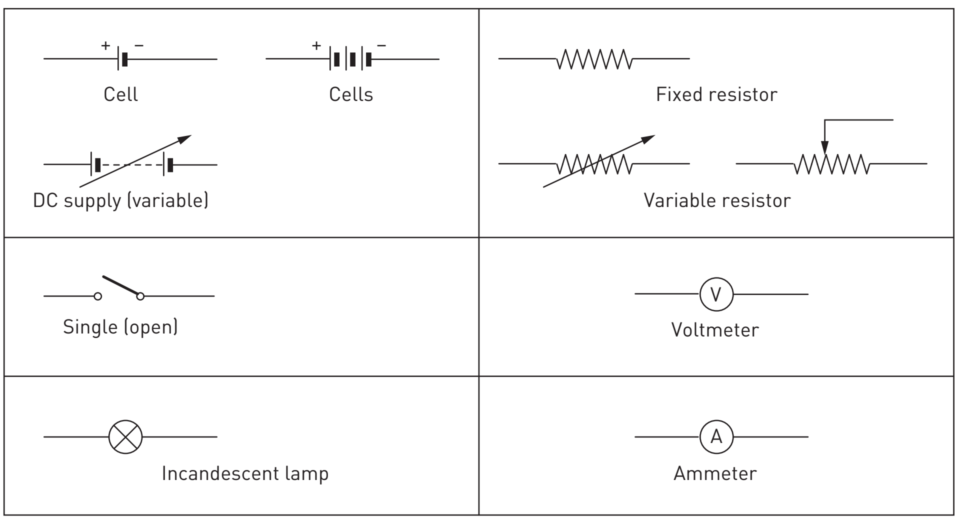

FIGURE 1 Circuit diagram symbols

Circuit analysis

This section will analyse a more complex electric circuit, making use of all circuit laws, electric meters and methods of connection discussed so far. You must be able to read unfamiliar electric circuits and carry out the necessary calculations to solve for unknown or required circuit component values. You must also be able to use the laws of circuit behaviour to predict voltages and currents at any point in a circuit.

The Worked example 9.2 illustrates the general steps that might be followed, but remember there is usually more than one way to the solution.

WORKED EXAMPLE 9.2

Consider the circuit shown in Figure 2.

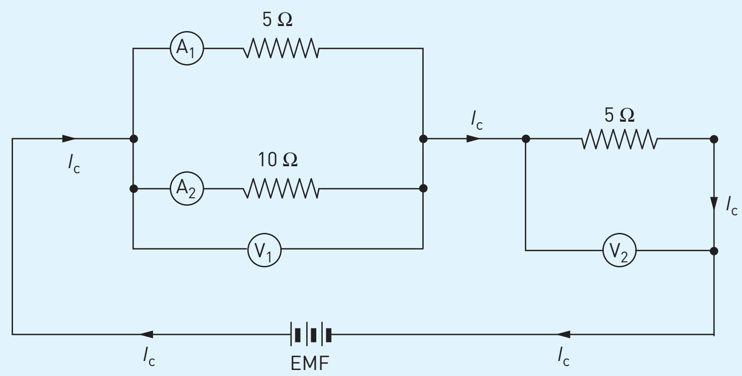

FIGURE 2 Circuit diagram. The battery consists of three cells each of 1.5 V.

Calculate:

a the circuit current, I_c, flowing from the battery.

b the voltage reading on V_1 and V_2.

c the current reading on ammeters A_1 and A_2.

d the battery EMF.

SOLUTION

Note the following about this circuit:

- The battery has three cells, each of 1.5 V, therefore EMF = 4.5 V.
- 10 Ω and 5 Ω resistors are in parallel, and this combination is in series with the 5 Ω resistor.
- The current readings in $I_1 + I_2$ will equal I_c (Kirchhoff's current law).
- The voltages across the 5 Ω and 10 Ω resistors will both be equal to voltage V_1.
- The sum of voltages $V_1 + V_2$ will equal the EMF, 4.5 V (Kirchhoff's voltage law).

a Calculate equivalent resistance of parallel combination, R_P:

$$\frac{1}{R_P} = \frac{1}{5} + \frac{1}{10} = \frac{3}{10}$$

$$R_P = 3.3\ \Omega$$

Calculate equivalent circuit total resistance in series with battery, R_t:

$$R_t = R_P + 5 = 3.3 + 5 = 8.3\ \Omega$$

Calculate total current flow, I_C, using Ohm's law:

$$I_C = \frac{V}{R_T} = \frac{EMF}{R_T} = \frac{3.5}{8.3} = 0.54\ A$$

b Now consider only the 5 Ω resistor. Apply Ohm's law to find the voltage V_2:

$$V_2 = I_C \times R = 0.54 \times 5 = 2.7\ V$$

Calculate the voltage V_1, using the loop law:

$$V_1 + V_2 = EMF$$

$$V_1 + 2.7 = 4.5$$

$$V_1 = 1.8 \text{ volts}$$

Thus, voltage V_1 = 1.8 V.

c Voltage V_1 = 1.8 V is the voltage drop across each resistor 5 Ω and 10 Ω in the parallel arm. Hence, calculate currents I_1 (in meter A_1) and I_2 (in meter A_2):

$V_1 = I_1 \times 5$

$1.8 = I_1 \times 5$

$I_1 = 0.36$ A

$V_1 = I_2 \times 10$

$1.8 = I_2 \times 10$

$I_2 = 0.18$ A

Notice that the sum of the currents I_1 and I_2 equals the circuit current I_C = 0.54 A, as required by Kirchhoff's law. It is also possible to redraw equivalent but simplified circuit diagrams at each step to further aid understanding of the analysis.

d EMF = 4.5 V (as calculated earlier)

Voltage dividers

Variable resistor as a potential divider (potentiometer)

To vary the input voltage during an Ohm's law experiment, you simply turn the knob on the power supply. The setting may say 12 V, and the actual voltage is usually somewhere close to this. But what if you wanted exactly 5.0 V, or needed less than 2 V, for an electronics experiment?

Schematically, a potential divider is used as in Figure 3. It consists of a variable resistor in which three terminals are used. It is also called a potentiometer.

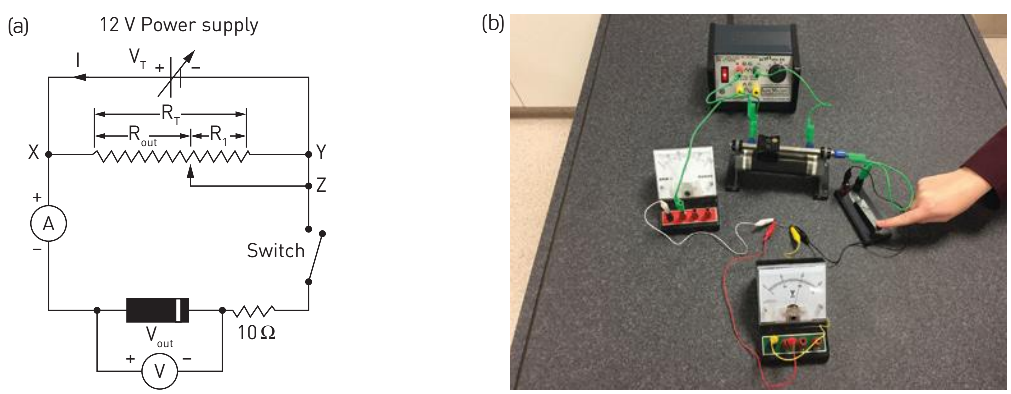

FIGURE 3 (a) Schematic for the testing of a diode using a potentiometer to select the desired voltages. (b) The same set-up as in the schematic – the slider is connected electrically to the terminal on the top right. Note that three terminals are used.

Variable resistor (rheostat)

If different values of resistance are required for a circuit, two terminals of a variable resistor are used. The variable resistor is then called a **rheostat**. Figure 4 shows a schematic for a variable resistor used as a rheostat, and its circuit symbol.

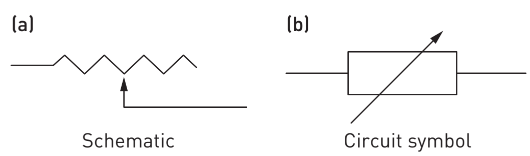

FIGURE 4 (a) Schematic and (b) circuit symbol for a variable resistor used as a rheostat.

SUGGESTED PRACTICAL
9.2 Circuits for real life purposes – using a fuse for protection
Go to your obook assess »

CHECK YOUR LEARNING 9.2

Describe and explain

1 **Sketch** circuit diagram symbols for resistor, rheostat, voltmeter, ammeter, cell, battery, switch and bulb.

2 **Explain** how a voltage divider works.

3 A student set up an electric circuit with two 25 Ω resistors in parallel, connected to a battery of EMF 12 V. The student wishes to calculate the total circuit current and the individual currents through each resistor. **Sketch** a circuit diagram the student would use and calculate the values for these currents.

Apply, analyse and interpret

4 **Consider** the electric circuit shown in Figure 5.

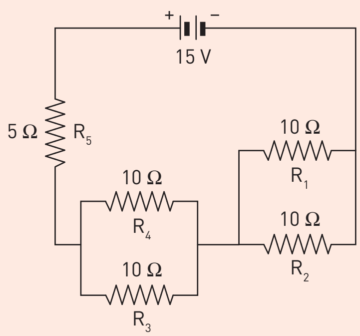

FIGURE 5 Circuit diagram

Calculate the current flowing through each resistor and the voltage drop across each resistor using the laws of circuit analysis. Fully describe your steps and redraw the appropriate equivalent circuits at each step.

5 A cell of voltage 10.0 V with negligible internal resistance is connected with two resistors in parallel as shown in Figure 6.

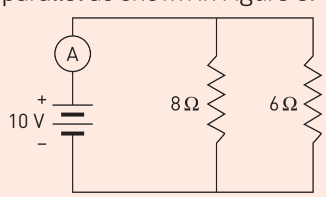

FIGURE 6 Two resistors in parallel

If the internal resistance of the ammeter is 1.5 Ω, **determine** the reading on the ammeter.

6 Students set up a circuit to measure the voltage vs current characteristics of two devices (labelled A and B) in turn. They increased the current through each in 20 mA increments and noted the voltage across it. The results are shown in the graph (Figure 7).

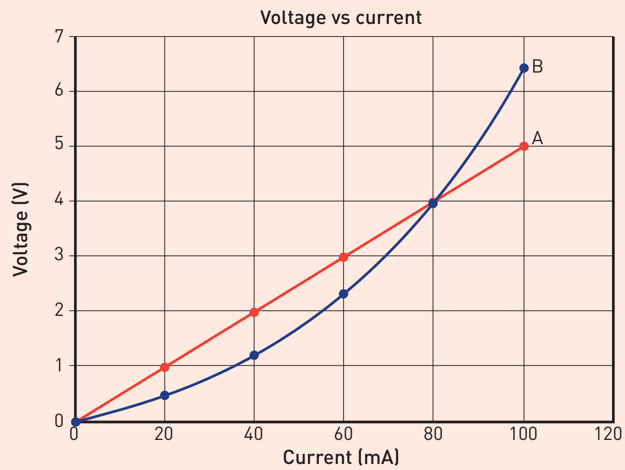

FIGURE 7 Graph of voltage vs current

a **Determine** if these are ohmic or non-ohmic devices and explain your reasoning.

The devices were then placed in parallel in a circuit as shown in Figure 8.

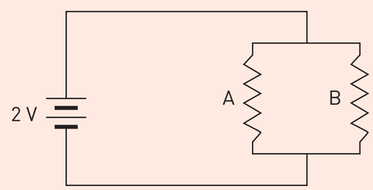

FIGURE 8 Parallel circuit

b **Calculate** the combined resistance of the two devices.

c **Calculate** the resistance of each device when the voltage is 4.0 V.

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  9.2 Circuits for real life purposes using a fuse for protection
- » Increase your knowledge
  Reading meter scales
- » Increase your knowledge
  Series and parallel circuits in action

9.3 Electrical energy and power dissipation

KEY IDEAS

In this section, you will learn about:

+ power dissipation.

In modern society, electrical energy can be easily converted into a whole range of other energy forms, such as heat, light, mechanical energy and electromagnetic energy (radio and television).

Electrical energy is generated in several ways – from the simple DC level with devices such as cells and batteries, through to AC generators of different types. Domestic and industrial AC electricity supply is often generated by coal-, oil- or gas-burning power stations. More recently, thermal, wind power and hydroelectric power stations are used. New developments in electricity production involves roof-mounted photovoltaic (PV) panels.

The basis of all forms of AC electric generators is the spinning coil induction turbine. Once the electrical energy is produced, AC transformers can change the voltage so it may be efficiently distributed via conducting cables around the countryside to factories and homes.

Power dissipation

When electric charge flows through a resistor, thermal heat is produced (as previously discussed). Electrical energy is being converted to thermal energy within the resistor, and this forms the basis of any electric appliance designed to produce heat, such as radiators, electric stove elements, hot water systems, electric blankets and electric kettles. In an electric light bulb, this resistive heating of the filament wire produces light energy.

Electrical energy is often converted into mechanical energy – for example, in any appliance that contains an electric motor. We refer to this loss of electrical energy as **power dissipation**.

power dissipation a measure of the rate at which energy is lost from an electrical system

Power dissipation formula

Whenever electrical energy conversion is occurring, electric charge, Q, is being moved through a potential difference, V. The earlier formula for voltage was $V = \frac{W}{Q}$, so $W = VQ$.

Power was defined as the rate of doing work: power (P) is work (W) divided by time (t), which is written as $P = \frac{W}{t}$. Another useful arrangement is $W = Pt$.

Putting these together:

$$P = \frac{W}{t} = \frac{V \times Q}{t} = VI\left(\text{as } \frac{Q}{t} = I\right)$$

$$P = VI$$

Power is the product voltage across an appliance multiplied by the current flow through the appliance. This formula is appropriate in both DC and AC voltage and current situations. The unit for electrical power is the watt (W), with 1 watt equivalent to a rate of energy transfer of 1 joule per second: 1 W = 1 J s^{-1}.

Other power formulas

Using Ohm's law, power dissipation can be calculated using the power rule:

$$P = VI$$
$$= (I \times R) \times I \text{ (}V\text{ replaced with }IR\text{)}$$
$$= I^2 R$$
$$P = I^2 R$$

Many domestic and industrial electric appliances state the power dissipation rating on their compliance plates. For example, a television rated 110 W will consume electrical energy at the rate of 110 joules per second. It is this energy usage that consumers must pay for as it is supplied by the electricity authority.

The common unit for electrical energy usage in domestic and industrial situations is the kilowatt hour (kW h). The electricity authority commonly refers to the kW h as a 'unit' of electricity – it represents the amount of electrical energy used by a device rated at 1 kilowatt over a period of 1 hour.

Study tip

Another useful power formula can be found on your obook assess.

WORKED EXAMPLE 9.3

a Calculate the power dissipated by an electric drill operating from the normal 240 V AC supply and drawing an operating current of 1.60 A.

b Calculate the monthly energy used by a television with a power rating of 110 W that is operating daily for 6.5 hours.

SOLUTION

a $P = VI = 240\ \text{V} \times 1.60\ \text{A} = 384\ \text{W}$

b Energy used daily (ensuring time is converted to seconds):

$W = P \times t = 110 \times 6.5 \times 60 \times 60 = 2.6 \times 10^6\ \text{J}$

Assuming a month has 30 days, the total energy used by the television is 7.7×10^7 J.

CHALLENGE 9.3A

Brightness of light bulbs

The formula $P = \frac{V^2}{R}$ implies that if the resistance (R) of a light bulb is decreased, the power consumption (P) will increase and hence the light bulb will glow brighter.

However, the formula $P = I^2 R$ implies that if R is decreased, P is also decreased and hence the bulb will get dimmer.

They can't both be right. What is your answer to this apparent anomaly?

FIGURE 1 A light bulb is an example of electrical energy being converted into light.

Light bulbs

Light bulbs are usually stamped with a maximum voltage rating and the current or power dissipated at that voltage. It gives you an idea of how bright they will be. For example, household light bulbs (both the old incandescent ones or the newer fluorescent, LED or halogen types) will be rated as 240 V but could be 20 W for low intensity or 40 W for a brighter one.

Figure 2 shows two bulbs with different ratings. The first is a 4.8 V, 0.3 A bulb (from a torch). When it is connected across a 4.8 V output and has reached its operating temperature (after about 0.15 s), the bulb will 'draw' a current of 0.3 A. From the formula $V = IR$, the hot resistance of the bulb is $\frac{V}{I} = \frac{4.8}{0.3} = 16\ \Omega$. When measured cold, the bulb has a resistance of 1.7 Ω. This shows the resistance increases with temperature.

The second bulb (from a car tail-light) is 12 V, 21 W. This means it has a power dissipation of 21 W when run at 12 V. From the formula $P = \frac{V^2}{R}$, the resistance when hot is $\frac{(12^2)}{21} = 6.8\ \Omega$. Its current would be $I = \frac{V}{R} = \frac{12}{6.8} = 1.8$ A.

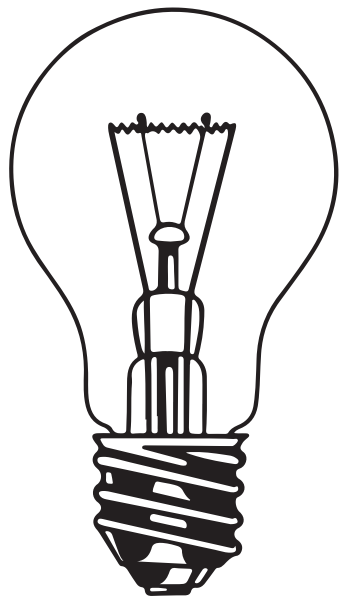

FIGURE 2 (a) 4.8 V, 0.3 A torch bulb; (b) 12 V, 21 W car tail-light bulb

School laboratory power supplies can deliver currents of about 5 A before they automatically switch off (or cut out). They have an overload switch for protection.

CHALLENGE 9.3B

Household lighting

Household incandescent bulbs are typically 240 V, 100 W. This means their hot resistance is $(240^2) \times 100 = 576\ \Omega$. They draw a current of $I = \frac{V}{R} = \frac{240}{576} = 0.4$ A.

Household fuses on lighting circuits are usually 10 A, so you could run 25 bulbs in parallel on the one circuit. However, when the bulbs are cold their resistance is 86 Ω. Show that each bulb would draw 2.8 A and just four bulbs should blow a 10 A fuse. Can you explain why the fuses don't blow?

CHECK YOUR LEARNING 9.3

Describe and explain

1 A torch bulb is rated as 6 V, 0.4 A. **Explain** what this means.

2 **Explain** how the formula $P = VI$ can be turned into $P = \frac{V^2}{R}$.

3 **Calculate** the power (dissipation) rating of a light bulb operating at 240 V and 0.6 A.

4 **Calculate** the resistance at normal operating conditions of the following appliances run from the 240 V AC mains:

  a 50 W television

  b 1 kW hair dryer

  c 100 W light bulb

5 A heater is connected to the normal mains 240 V supply. If the resistance element has a value of 8 Ω, **calculate** how much electrical energy is supplied to the heater in 5 minutes.

6 **Calculate** the electrical energy produced by an electric kettle with a power rating of 2100 W used for 2 minutes and 20 seconds.

Apply, analyse and interpret

7 **Clarify** how many joules per second is a watt.

8 **Determine** how many seconds it would take a kettle with a power rating of 1800 W to produce 36 000 J.

9 **Determine** the current a heater will draw if it has a 1 kW power rating and is connected to a 240 V electrical supply.

10 You want to use 200 000 J of electrical energy in a microwave oven of 900 W power rating.

  a **Determine** how long it should be turned on for.

  b **Calculate** the current drawn from a 240 V supply.

Investigate, evaluate and communicate

11 You want to use 200 000 J of electrical energy in a kettle of 1800 W power rating. **Decide** how long it should be turned on for.

12 **Propose** the main way power is 'dissipated' in an electric toaster.

13 In modelling a household lighting set-up, students set up the circuit shown in Figure 3. The bulbs were all labelled as 4.8 V, 0.3 A.

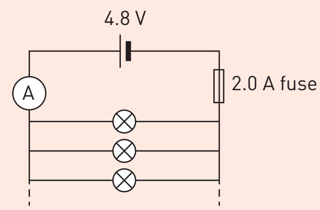

FIGURE 3 Circuit modelling a household lighting set-up

  a **Predict** the maximum number of bulbs that could be used in parallel before the fuse will blow.

  b If the bulbs were replaced with 4.8 V, 2 W types, **calculate** how many could now be used before the fuse blows.

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  Check your learning 9.3
- » Challenge
  9.3A Brightness of lightbulbs
- » Challenge
  9.3B Household lighting
- » Increase your knowledge
  An alternative power formula

SCIENCE AS A HUMAN ENDEAVOUR

9.4 Powering the digital age

KEY IDEAS

In this section, you will learn about:

+ the importance of a reliable power supply.

We need a reliable supply of electricity for our society to function in this digital age. Computers, smartphones and the internet may have changed the world, but none would be possible without a reliable supply of electricity.

In Australia, household electricity consumption varies over the year with a big peak in July and a lesser one in December/January. On top of this, demand is increasing every year despite the increased contribution of electricity generated by solar panels.

Electricity suppliers must be able to meet peak demands, such as in the summer holidays when air-conditioner use adds to the demand. Electricity suppliers all have reserve capacity and can share electricity around the country through a national network. This helps them to manage power requirements for unusually hot or cold days in one part of the country. However, extreme weather events add unpredictable demands that are hard to cope with. In such times we can get unintentional 'brown-outs' where the voltage drops below the expected range and appliances work intermittently.

Why use AC for power distribution?

All large power-distribution systems in Australia (and in most of the world) are alternating current (AC). Moreover, the power is transmitted at much higher voltages than the 240 V AC we use in homes and industry. Economies of scale make it cheaper to build a few very large electric power generation plants than to build numerous small ones. As a result, electricity must be transmitted over long distances and we want to ensure not too much energy is wasted on the way.

Queensland has 15 000 km of transmission network going out to 2 million customers. High voltages can be transmitted with much smaller power losses than low voltages because they are sent at much lower currents. Power losses are given by the formula $P = I^2R$, so the lower the current I, the lower the power loss.

A power station produces electricity at 275 kV or 330 kV. This is sent along wires on huge steel towers until it is 'stepped down' at substations to 110 kV then to 33 kV. At suburban sub-stations, this is stepped down further to 11 kV and sent around the streets in wires on wooden power poles. For safety reasons, the voltage is then reduced from 11 kV to 415 V by small transformers attached to the poles in your street. The 415 V is distributed in the lower four wires outside your home. Electricity suppliers connect houses to two of these wires to give 240 V into your home.

It is much easier to increase and decrease AC voltages than DC, so AC is used in most large power-distribution systems. The 'stepping down' is done by transformers – in Queensland alone there are 48 000 transformers.

WORKED EXAMPLE 9.4

a What current is needed to transmit 100 MW of power at 275 kV?

b What is the power dissipated by the transmission lines if they have a resistance of 1.00 Ω?

SOLUTION

a $P = VI$

$I = \frac{P}{V} = \frac{(100 \times 10^6)}{(275 \times 10^3)} = 364\text{ A}$

b Power losses are given by $P = I^2 R = 363^2 \times 1 = 131\,769\text{ W}$.

As a percentage of input power (100 MW), this is $\frac{131\,769}{(100 \times 10^6)} \times 100 = 0.13\%$ (2 sf)

CHECK YOUR LEARNING 9.4

Apply, analyse and interpret

1 The demand for electricity varies during the day. It is highest in the morning around breakfast time and again in the early evening when people are arriving home. The graphs in Figure 1 illustrate usage patterns for (a) a home where the occupants are out most of the day, and (b) a business.

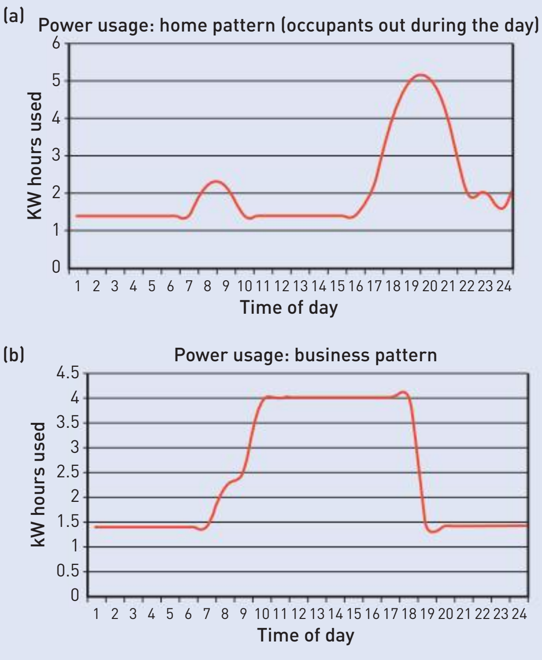

FIGURE 1 Energy usage in homes and businesses during the day

a **Explain** the reason for the shape of each graph and the differences between them.

b **Determine** the maximum power used in each case and at what time it is used.

Evaluate, investigate and communicate

2 In the previous text, a claim has been made above that 'High voltages can be transmitted with much smaller power losses than low voltages because they are sent at much lower currents'. **Identify** three relevant scientific concepts associated with this claim and **assess** how they relate to energy losses.

3 'Electricity from a battery is 100 times more expensive than the electricity from your power point'. Is this true? **Design** an experiment to find out how much electricity you can get out of a 1.5 V AA battery and compare it with the 240 V mains supply (10 cents per kWh).

Check your obook assess for these additional resources and more:

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» Increase your knowledge
Heating different substances

» Increase your knowledge
Science as a Human Endeavour: Electric lighting

» Weblink
Electricity

CHAPTER 9

Review

Summary

9.1

- The three important electrical circuit laws that allow detailed analysis of electric circuits are Ohm's law, Kirchhoff's current law and Kirchhoff's voltage law.
- Kirchhoff's current law states that at any node in an electrical circuit, electric charge is conserved such that the sum of the electric currents flowing into a node is equal to the sum of electric currents flowing out of that node.
- Kirchhoff's voltage law states that the energy inputs in a circuit equal the sum of energy output from loads in the circuit such that the directed sum of the electric potential differences around any closed network is zero.

9.2

- Electric circuits can be represented by use of symbols.
- Series and parallel circuits can be represented as equivalent circuits.
- Rheostats are two-terminal variable resistors that provide a variable resistance.
- Potentiometers are three-terminal variable resistors that can divide voltages for use in practical circuits.

9.3

- Power dissipation is a measure of the rate at which energy is lost from an electrical system.

9.4

- Electricity is supplied to the home as energy in units called kilowatt hours.
- Our society needs a reliable supply of electricity to function in this digital age. Computers, smartphones and the internet may have changed the world, but none would be possible without a reliable supply of electricity.
- Increases in the use of household electrical devices during extreme weather conditions create supply problems, causing brownouts and power failures.

Key terms

- Kirchhoff's current law (KCL)
- Kirchhoff's voltage law (KVL)
- power dissipation

Key formulas

Kirchhoff's voltage law	$V_t = V_1 + V_2 + \ldots + V_n$
Kirchhoff's current law	$I_t = I_1 + I_2 + \ldots + I_n$
Overall resistance (resistors in series)	$R_t = R_1 + R_2 + \ldots + R_n$
Overall resistance (resistors in parallel)	$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots + \frac{1}{R_n}$
Power and Ohm's law	$P = VI$ $P = I^2 R$ $P = \frac{V^2}{R}$

Revision questions

The relative difficulty of these questions is indicated by the number of stars beside each question number: ★ = low; ★★ = medium; ★★★ = high.

Multiple-choice

1 The power of an electric bulb drawing 1.2 A current at 6.0 V is:

A 0.2 W
B 0.5 W
C 5 W
D 7.2 W.

2 For the circuit in Figure 1, which is the best statement of the arrangement shown:

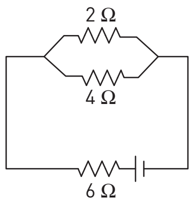

FIGURE 1 Circuit diagram

A 2 Ω , 4 Ω and 6 Ω are in series
B 2 Ω and 4 Ω are in parallel and the combination is in parallel with 6 Ω
C 2 Ω , 4 Ω and 6V Ω are in parallel
D 2 Ω and 4 Ω are in parallel and 6 Ω is in series.

3 The resistance across AB in the circuit in Figure 2 is:

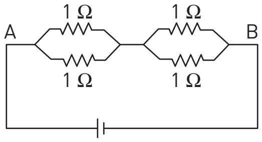

FIGURE 2 Circuit diagram

A 1 Ω
B 2 Ω
C 4 Ω
D 5 Ω.

4 When current *I* flows through resistance *R* for time *t*, the electrical energy spent is given by:

A IRt
B I^2Rt
C IR^2
D $\frac{I^2R}{t}$.

5 Three resistors ($R_1 = 3\ \Omega$, $R_2 = 6\ \Omega$, and $R_3 = 9\ \Omega$) are connected in series to each other and to a 36 V battery, as shown in Figure 3.

What is the ammeter reading after the switch is closed?

A 6 A
B 5 A
C 4 A
D 2 A

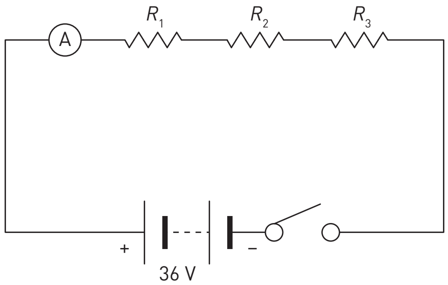

FIGURE 3 Three resistors in series

Short answer

Describe and explain

★**6** **Recall** the names of the circuit symbols in Figure 4.

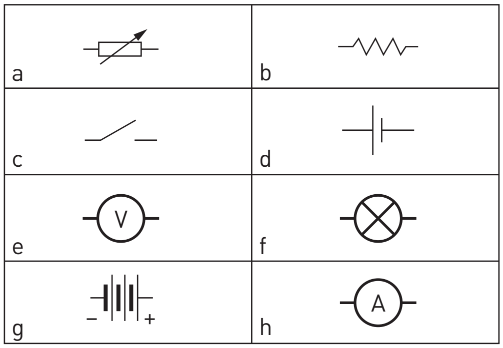

FIGURE 4 Circuit symbols

★**7** **Recall** what characteristic enables you to differentiate between a series circuit and a parallel circuit.

★**8** **Define** electromotive force and power dissipation.

★**9** **Explain** why birds can safely touch overhead power cables but humans standing on the ground cannot.

★**10** **Describe** Kirchhoff's current law and Kirchhoff's voltage law.

★**11** Overhead wires are isolated from the power poles by ceramic or plastic devices. **Define** the term 'isolated' in this context.

★**12** **Explain** why appliances are protected by a fuse and explain how the fuse provides this protection.

★ **13** In Figure 5, with the switch open, state which circuit would light lamps Q and R but not lamp P and **explain** your reasoning.

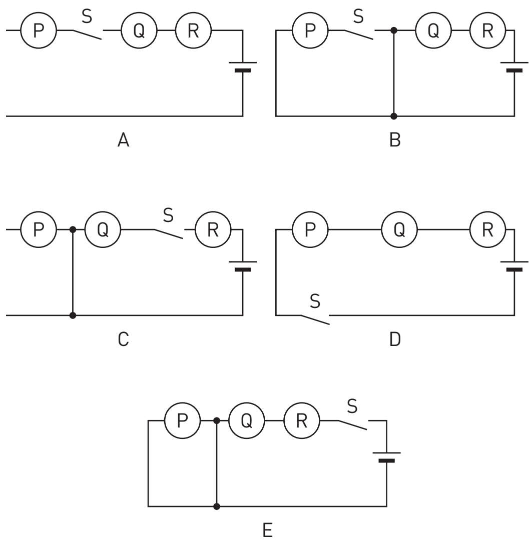

FIGURE 5 Circuit diagrams

★ **14** An electric jug is marked 240 V, 1.6 kW. When in normal use, **calculate** the current drawn by the heating element.

★ **15** **Calculate** the energy gained by a charge of 18 C when it passes through a source of EMF of 12 V.

★ **16** **Calculate** the largest number of 100 W lamps connected in parallel that can safely be run from a 240 V supply with a 5 A fuse.

★ **17** An automatic washing machine is labelled 240 V, 960 W. **Calculate:**

a the operating current in normal use

b the operating resistance in normal use.

★ **18** For the circuit in Figure 6, **calculate** the following:

a battery voltage

b circuit current at the points labelled X, Y and Z

c reading on the voltmeter, V.

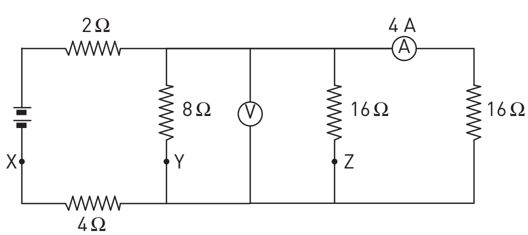

FIGURE 6 Circuit diagram

★★★ **19** Figure 7 shows a complex circuit.

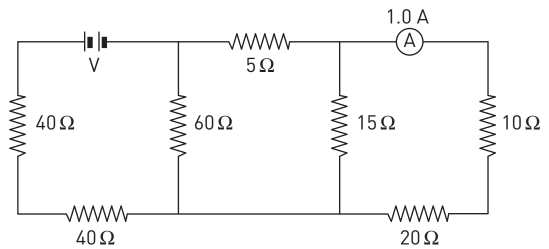

FIGURE 7 Complex circuit diagram

Calculate the following values:

a total circuit resistance

b voltage drop across the 60 Ω resistor.

Apply, analyse and interpret

★★ **20** **Determine** how much energy would be produced by a 12 V heater that drew a current of 4 A for 2 minutes.

★★ **21** The accumulator of a car produces 12 V. If the car lights at the sides and rear are each rated for 12 V but the two interior lights are only rated at 6 V, **determine** if the lights are connected in series or in parallel.

★★ **22** How does the resistance of a 60 W, 240 V light bulb compare with that of a 25 W, 240 V light bulb? **Deduce** which has the thicker bulb filament.

★★ **23** The headlights on a car operate typically at 60 W and the parking lights typically at 5 W. Assuming there are two main headlights and four parking lights, **determine** the length of time it will take to discharge a battery if the lights are left on. This particular battery can supply a total of 216 000 J.

★★★ **24** If the supply is 240 V, **determine** what size fuse (8 A or 15 A) should be used in a plug connected to each of the following:

a 100 W television

b 800 W electric iron

c 2.2 kW kettle.

Investigate, evaluate and communicate

★ **25** For circuit analysis, **decide** which of Kirchhoff's laws would be applied if there were two resistors:

a in series **b** in parallel.

★★ **26** Assume you have only five 12 Ω resistors.

a **Devise** a circuit that would let you connect some or all of the resistors to produce an effective total resistance of 4 Ω.

b **Decide** the maximum and minimum resistance you could have using all the resistors.

★★**27** Overhead power wires are made from aluminium. Given that steel is cheaper than aluminium, **assess** why it is not feasible to make these power wires from steel.

★★**28** **Devise** and **sketch** a circuit diagram that shows how you might measure the operating resistance of a single light bulb using a battery, ammeter and/or voltmeter.

★★**29** The resistances R_1, R_2, R_3 and R_4 in Figure 8 are all equal in value. Assuming the connecting wires in the circuit have negligible resistance, **predict** what you would expect the voltmeters A, B and C to read.

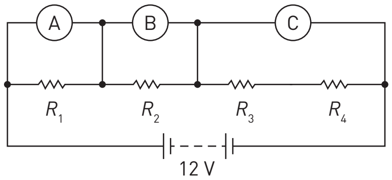

FIGURE 8 The resistors have equal resistance

★★★**30** In each of the circuits in Figure 9, **propose** the readings on all voltmeters and ammeters as well as the total circuit equivalent resistance.

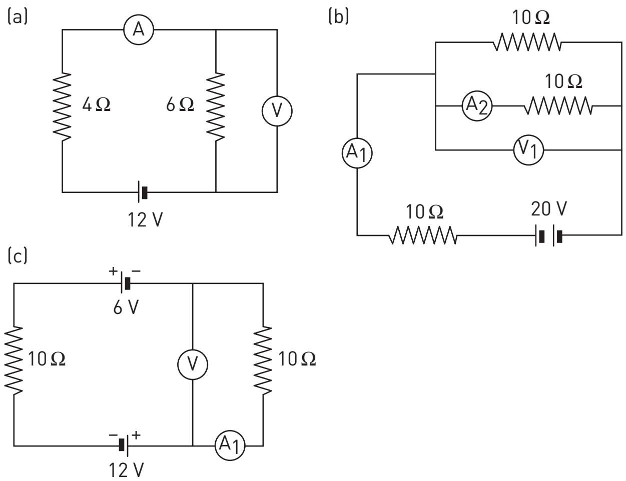

FIGURE 9 Circuit diagrams

★★★**31** Figure 8 shows a graph of potential difference versus current for two different electrical devices, A and B.

a **Assess** whether either device is an ohmic resistor.

b If A and B are connected in series and a current of 200 mA passes through them, **determine** the total potential difference across A and B.

c If A and B are joined in parallel, **determine** what potential difference across them would produce a current in A that is half the current in B.

d **Calculate** the resistance of device A and compare with this to the resistance of B with a voltage of 15 V applied.

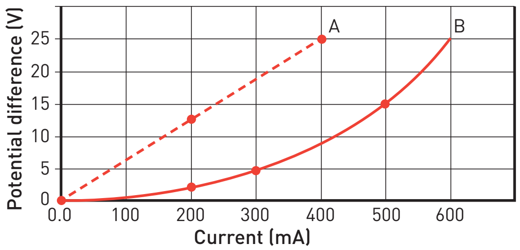

FIGURE 10 Graph of potential difference versus current for device A and device B

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Chapter 9

UNIT 1

Practice exam questions

Thermal, nuclear and electrical physics

Multiple-choice

1 The temperature of a gas is a measure of the molecules' average:

A velocity.

B momentum.

C kinetic energy.

D frequency of collisions.

2 A 40 kg object is heated from 10°C to 25°C, which required 30 000 J of thermal energy. The specific heat capacity of the object is:

A 25 J kg^{-1} K^{-1}

B 50 J kg^{-1} K^{-1}

C 75 J kg^{-1} K^{-1}

D 100 J kg^{-1} K^{-1}

3 A substance can be depicted in three different states as shown in Figure 1.

FIGURE 1 Three states of a substance

If the substance is in state B and is cooled down and undergoes a phase change, which of the following occurs to the substance?

A It changes to state A.

B It stays as state B.

C It changes to state C.

D It changes to a liquid.

4 Which of the following lists the particles associated with radioactive decay in order of **increasing** ionising power?

A α, β, γ

B γ, α, β

C β, α, γ

D γ, β, α

5 The current in a resistor is measured as 2.00 A ± 0.02 A. Which of the following correctly identifies the absolute uncertainty and the percentage uncertainty in the current?

TABLE 1

	Absolute uncertainty	Percentage uncertainty
A	±0.02 A	±1%
B	±0.01 A	±0.5%
C	±0.02 A	±0.01%
D	±0.01 A	±0.005%

6 An Ohm's law experiment was conducted and the results plotted as the graph in Figure 2.

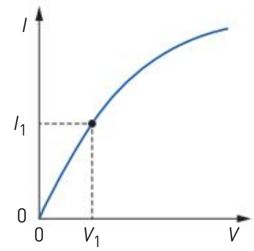

FIGURE 2 Graph of Ohm's law experiment results

Which of the following shows the resistance of the resistor used in the experiment when the current $I = I_1$?

A The slope of the line at the point (V_1, I_1)

B The slope of the line from 0,0 to the point (V_1, I_1)

C $\frac{V_1}{I_1}$

D $\frac{I_1}{V_1}$

7 Two wires *P* and *Q* are the same length, have a circular cross-section and are made of the same metal. The diameter of *P* is twice the diameter of *Q*.

What is the ratio of $\frac{R_Q}{R_P}$?

A 0.25 **B** 0.50

C 2.0 **D** 4.0

8 Two 20 Ω resistors are connected as shown in Figure 3.

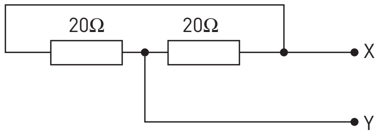

FIGURE 3 Two resistors are connected

What is the resistance between points X and Y?

A 0 Ω **B** 10 Ω

C 20 Ω **D** 40 Ω

Short answer

9 Construct a balanced equation for the alpha decay of Po-214.

10 A particular nuclear reaction produces 100 MJ of energy. Calculate the loss of mass in kg during the reaction.

11 A simple electric circuit is set up and the cell supplies 5.1×10^{-19} J to each electron in moving it around the circuit. Demonstrate that the EMF of the cell is 3.2 V.

12 A circuit is set up as in Figure 4. Calculate the current in the 800 Ω resistor.

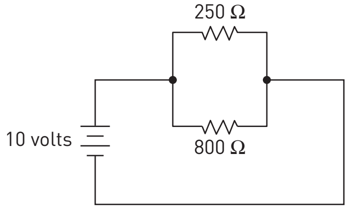

FIGURE 4 A circuit diagram

13 A 300 W electrical heater is placed in a beaker containing 0.25 kg of water at a temperature of 18°C. The heater is switched on for 120 seconds, after which time the temperature of the water is 45°C. The thermal capacity of the beaker is negligible, and the specific heat capacity of water is 4.2×10^3 J kg^{-1} K^{-1}.

a Interpret the data to determine how efficient the transformation is of electrical energy to thermal energy.

b Evaluate the experiment to propose the source of any losses or gains of energy.

14 An athlete loses 1.8 kg of water from her body through sweating during a training session that lasts 1 hour. Predict the rate of energy loss by the athlete due to sweating. The specific latent heat of vaporisation of water is 2.3×10^6 J kg^{-1}.

15 A researcher with a Geiger counter measures 200 counts per minute coming from a radioactive source at midday. At 3:00 pm, she finds that this has dropped to 25 counts per minute. Determine the half-life of the radioactive source.

16 An isotope of neptunium is np-241, which has a half-life of 14 minutes. A sample of Np-241 has an initial activity of 22×10^{10} Bq.

a On a copy of the graph in Figure 5, sketch a line to show the change in activity with time.

b Predict the activity of the sample after 90 minutes.

c Deduce the time that would have elapsed for the activity to be 2×10^{10} Bq.

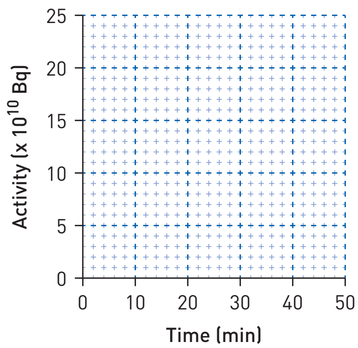

FIGURE 5 Show the change in activity with time.

17 A student is investigating series and parallel resistance in a laboratory experiment. She sets up the circuit shown in Figure 6 and adjusts the power supply until a current of 6.0 A is produced.

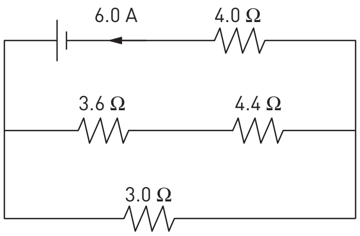

FIGURE 6 Circuit set-up

a Calculate the effective resistance of the circuit.

b Calculate the potential difference across the 3.0 Ω resistor.

UNIT 2
LINEAR MOTION AND WAVES

FIGURE 1 The force of gravity pulls skydivers towards the ground.

An understanding of linear motion, whether it is cars driving along roads or particles moving up and down in waves, underpins modern society's transportation and communication. With linear motion, Newton's laws relating displacement, velocity, acceleration and time allow calculation of the motion of objects from nuclear particles to spaceships. The role of gravity in providing an accelerating force on objects enables calculations about the motion of dropped and thrown objects – such as time of flight, maximum height and impact speeds. The laws of conservation of energy and momentum enable us to further predict the motion of objects whether they are a nucleus exploding or two cars colliding.

The motion of waves helps explain mechanical waves on Slinkys and strings, and sound waves in open and closed pipes and in musical instruments. This is in contrast to electromagnetic waves – waves that require no medium for their transmission and are familiar as visible light with its rainbow colours, microwaves for cooking and X-rays for medicine. The realm of light waves enables experiments with lenses and mirrors to confirm laws of reflection and refraction. Experiments with thin slits help to explain the processes of diffraction and interference. Along with polarisation, these show the power of the wave model for light.

This unit will show that physics can explain natural phenomena and be used to predict the behaviour of matter and waves in a broad range of scenarios.

UNIT 2 TOPICS

Topic 1	Linear motion and force	Chapters 10–13
Topic 2	Waves	Chapters 14–16

Unit objectives

→ Describe and explain linear motion and force, and waves.
→ Apply understanding of linear motion and force, and waves.
→ Analyse evidence about linear motion and force, and waves.
→ Interpret evidence about linear motion and force, and waves.
→ Investigate phenomena associated with linear motion and force, and waves.
→ Evaluate processes, claims and conclusions about linear motion and force, and waves.
→ Communicate understandings, findings, arguments and conclusions about linear motion and force and waves.

Source: *QCAA Physics General Senior Syllabus 2019*

CHAPTER 10

Linear motion

People have been watching and recording things move for thousands of years. The motions of the heavens are some of the oldest recorded observations we have. More recently, a need to measure the speed of advancing armies or athletes or ships required better ways of measuring distance and time. Over the centuries, measurements became more accurate and now form the basis of modern physics. We can now measure distances and times to incredible accuracy.

OBJECTIVES

- → Define the terms vector and scalar, and use these terms to categorise physical quantities, e.g. velocity and speed.
- → Calculate resultant vectors through the addition and subtraction of two vectors in one dimension.
- → Define the terms displacement, velocity and acceleration.
- → Compare and contrast instantaneous and average velocity.
- → Describe the motion of an object by interpreting a linear motion graph.
- → Calculate and interpret the intercepts and gradients (and their uncertainties) of displacement-time and velocity–time graphs, and the areas under velocity–time and acceleration–time graphs.
- → Solve problems involving the equations of uniformly accelerated motion in one dimension.
- → Recall that acceleration due to gravity is constant near the Earth's surface.

Source: *Physics 2019 v1.2 General Senior Syllabus Queensland Curriculum & Assessment Authority*

FIGURE 1 Is it important to be able to time swimming races to one-thousandth of a second?

MAKES YOU WONDER

Sometimes the motion of objects doesn't seem to make sense. In this chapter you will learn about concepts of linear motion that will help to answer questions such as:

→ If we live on a world that is round, why do we not fall off? What evidence is there that Earth is round and not flat as some people believe?

→ Before the time of astronomer Copernicus, most people believed that Earth was stationary and the Sun moved around it. We now understand that Earth is moving around the Sun. How do we know this?

→ Earth moves in an almost circular orbit and never slows down. Most objects in the world seem to travel in straight lines and slow down. Why is Earth different?

PRACTICALS

MANDATORY PRACTICAL	**10.1** Acceleration due to gravity on Earth's surface
MANDATORY PRACTICAL	**10.2** Constructing and interpreting displacement-time and velocity-time graphs

10.1 Vectors and scalars

KEY IDEAS

In this section, you will learn about:

- how to use the terms vector and scalar to categorise physical quantities
- what a vector quantity is and how it is represented.

To completely specify a physical quantity, you cannot just state its magnitude. To fully describe the motion of an object you need to state its speed and the direction it is heading. When these are both known, they combine to form an example of a **vector quantity**.

vector quantity
a quantity that has both magnitude and direction

The word 'vector' comes from the Latin *vectus*, a form of the verb meaning 'to carry' (such as to carry extra information, data or disease). In biology, a vector is an organism that carries disease from one place to another (for example, a mosquito is the vector for malaria). In physics, a vector means a quantity that needs both **magnitude** and **direction** to specify it fully. Displacement, velocity, acceleration and force are examples of vector quantities.

Quantities that have magnitude but do not include a direction are called **scalar quantities**. Distance, speed, mass and time are all scalar quantities. Scalar quantities require no statement about direction. For example, time = 3.5 s, mass = 25.5 kg and current = 2.0 A are scalar quantity measurements — no direction has to be specified. The word 'scalar' comes from the Latin *scalaris* meaning 'pertaining to a ladder'. This refers to the stepwise change in the size of something without any reference to direction.

scalar quantity
a quantity that has a magnitude but no direction

TABLE 1 Scalar and vector quantities

Scalar	Vector
Length	Displacement
Speed	Velocity
Time	Acceleration
Volume	Force
Mass	Weight
Energy	Momentum
Frequency	Torque
Pressure	Moment
Power	Electric current
Temperature	Electric field
Charge	Magnetic flux density

Students often ask, 'Is temperature a vector quantity, because you can have negative and positive temperatures?'. For example, liquid nitrogen boils at –198°C. The answer is no, temperature is a scalar quantity. The +/– signs do not indicate a direction but simply a point on a scale. Temperature is a scalar quantity, even though it can be negative.

Co-ordinate systems for representing direction

The simplest coordinate system we can use to indicate direction in one dimension is shown in Figure 1. For the first part of this chapter we are concerned only with motion in the horizontal (left and right) direction. Later, we will be looking at objects moving in the vertical (up and down) direction.

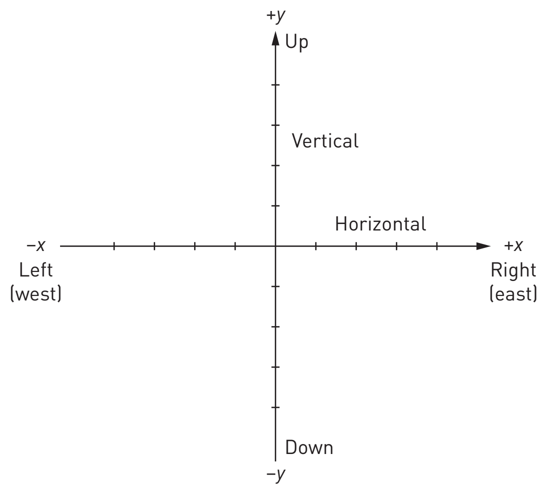

FIGURE 1 Coordinate system to indicate direction in one dimension.

Horizontal plane

In the horizontal plane, the coordinate system is a number line with forward motion to the east (E) or to the right being called positive (+). Backwards motion is depicted being to the west (W) or to the left and is called negative (–). We can use a number line as shown in Figure 2.

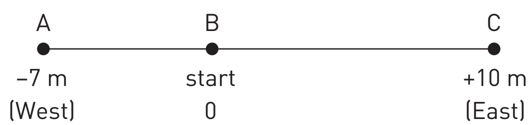

FIGURE 2 A number line can be used to depict left/right horizontal motion.

If we consider the position of B to be the zero (0) point, then the position of C is 10 m E or simply +10 m. Similarly, the position of A is 7 m W or –7 m.

Vertical plane

In the vertical plane, we represent up and down on the vertical axis (y-axis). A ball dropped off a cliff can be said to be heading in the negative direction (downwards). Figure 3 shows a ball at the top of a cliff being thrown vertically upwards. It starts at 0 m and reaches a height of +30 m, and so has travelled a distance of 30 m in the positive (+) direction, which is upwards.

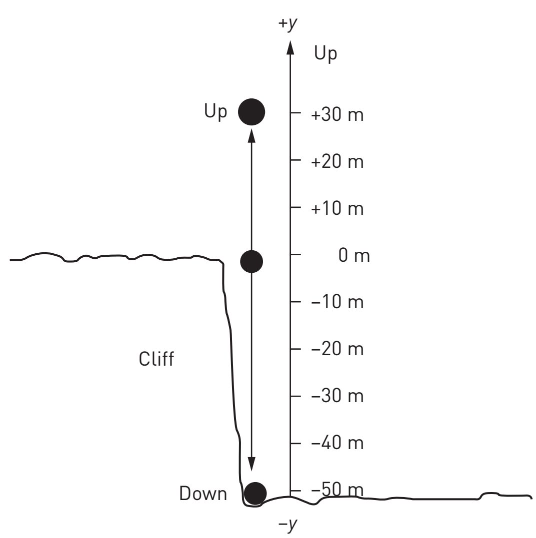

FIGURE 3 Vertical motion is represented as up/down on the vertical axis

Figure 3 also shows a ball being dropped from the top of a cliff (at 0 m) and landing at the base below at a position marked as –50 m. It has travelled 50 m in the negative (–) direction.

Once you have chosen a coordinate system for a question, you should not change it. We will not be using the vertical coordinate system until later in this chapter.

Representation of vector quantities

A vector quantity can be represented in two ways:

- pictorially
- symbolically.

Pictorially

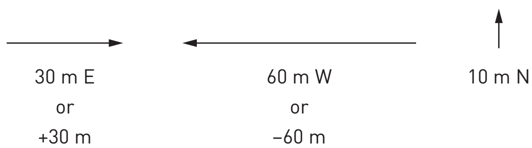

FIGURE 4 Vectors represented by 'directed line segments'

When representing a vector pictorially, the length of the arrow represents the magnitude of the vector and the arrowhead points in its direction. It is called a **directed line segment**.

directed line segment
an arrow representing a vector in which the arrowhead represents the direction of the vector, and the length represents the magnitude

For example, the three vectors in Figure 4 represent a person who has walked 30 m east, 60 m west and 10 m north respectively.

When vectors do not lie along the compass points (N, E, S, W), angles need to be specified. Figure 5 shows how the direction is indicated.

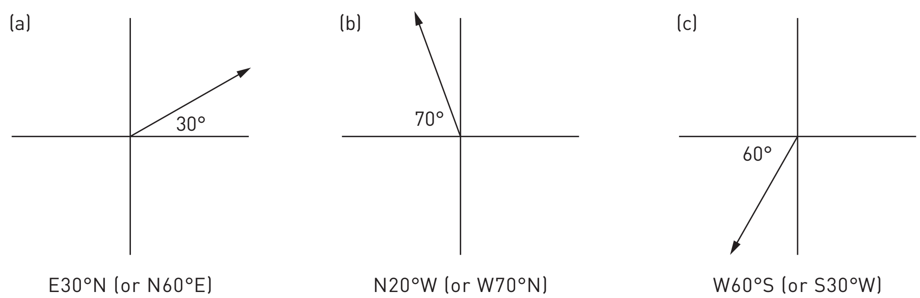

FIGURE 5 Angles must be specified when vectors do not lie along the compass points

Study tip

You must be able to use both vector conventions (symbolic and pictorial) – it is up to you which one you prefer. Remember to define the positive and negative directions.

Students often find it hard to work out the directions. Think of diagram A in Figure 4 as saying: the vector was pointing east but was rotated 30° to the north. You could also say it was pointing N but rotated 60° to the East (N60°E). They mean the same.

Symbolically

The other way to represent a vector is by using a letter with an overhead arrow. To indicate that the velocity of an object is 15 m s^{-1} in the west (W) direction, we would write:
$\vec{v} = 15\ \text{m s}^{-1}$ W or $\vec{v} = -15\ \text{m s}^{-1}$.

MANDATORY PRACTICAL

10.1 Acceleration due to gravity on Earth's surface
Go to page 482 »

CHALLENGE 10.1

Displacement of a cat

You are required to consider vector quantities in one dimension only; that is, in a straight line. However in Unit 3 you will need to consider vectors in two dimensions, and then in advanced (university) physics – in three dimensions. Here's a taste of 1-D, 2-D and 3-D vector addition.

A cat goes for a walk. It starts at Point A and goes 10 m north to the base of a tree (Point B). It climbs 5 m vertically up the tree and then heads east along a branch for a distance of 5 m and stops at point D.

Determine the displacement of the cat at:

a point B

b point C

c point D

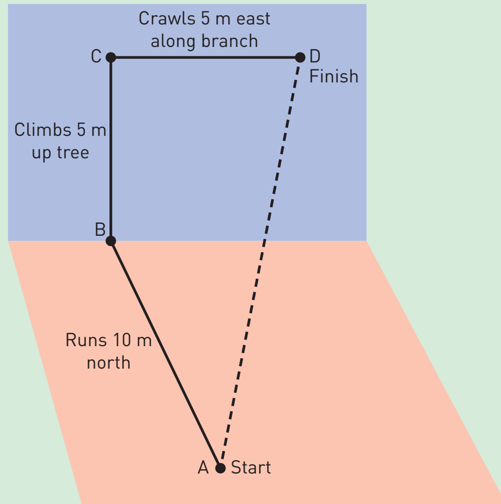

FIGURE 6 The path a cat takes on its walk

CHECK YOUR LEARNING 10.1

Describe and explain

1. **Define** vector quantity and scalar quantity.
2. **Recall** an example of a vector quantity and a scalar quantity.
3. **Explain** if the time of day is a vector or a scalar quantity.
4. **Explain** how you would symbolically represent the velocity of someone who was at rest.
5. **Sketch** the following vector quantities on a directed number line:
   a 30 m E **b** 100 m W
6. **Sketch** the following vector quantities using vectors (directed arrows):
   a 60 m W **c** 60 m N30°E
   b 30 m N **d** 30 m S60°E

Apply, analyse and interpret

7. A person's position is represented by the vector 40 m E. **Classify** which part of the vector represents the magnitude and which part represents the direction.

Investigate, evaluate and communicate

8. If you wanted to depict the downwards direction as positive, **decide** if there would be anything stopping you.
9. You can run around an oval at constant speed, but your direction keeps changing. **Decide** whether speed is a scalar or vector quantity.

Check your obook assess for these additional resources and more:

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Check your learning 10.1

» **Mandatory practical**
10.1 Acceleration due to gravity on Earth's surface

» **Challenge**
10.1 Displacement of a cat

» **Video tutorial**
Explanation of vectors and scalars

10.2 Distance and displacement

KEY IDEAS

In this section, you will learn about:

- the concept of displacement
- addition and subtraction of vectors.

Being able to measure distances, angles and time has always been important, even in ancient times. Often it was for religious reasons (worshipping Sun gods), and other times it was an attempt to plot the motion of the stars (a primitive astronomy). However, sometimes it had a more practical purpose – measuring distance was important in the construction of houses, building canals and cultivating fields.

Distance

distance
the total length of the pathway taken between the origin and the destination point; symbol *d*

Whereas length is a measure of how long or wide an object is, we use the term **distance** to describe how far an object has moved. A person travelling from one city to another may have moved a distance of 1200 km.

In physics, we need to be able to state not only distance but also the direction. For example, we may want to say that a person has moved 1200 km north. We are now describing a person's displacement – a vector quantity that combines magnitude and direction.

Displacement

displacement (linear motion)
a vector quantity representing the change in position irrespective of the path actually taken between the two points (symbol: *s*; SI unit: metre; unit symbol: m)

Displacement is the change in position of an object in a given direction. Think of it as the position measured relative to the origin. In simple terms. displacement is a change in position in a stated direction. It is given the symbol *s* for the Latin word *spatium*, meaning distance or space.

In Figure 1, if you started at point X and walked 8 m east to point Z and then turned around and walked 5 m west to point Y, you would have covered a distance of 13 m. However, you would only have a change of position (displacement) of 3 m east. That is, your position would only have changed by 3 m to the east. In symbols, this could be written as $\vec{s}$ = 3 m E. Note that the '*s*' has an arrow overhead to indicate it is the symbol for a vector quantity. Displacement is a vector quantity presenting the location of the destination relative to the origin of motion only, irrespective of the path actually taken between the two points.

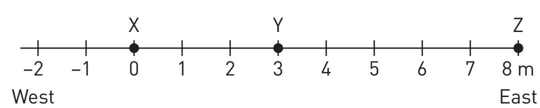

FIGURE 1 If you started at X and ended at Y, your displacement could be written as $\vec{s}$ = 3 m E.

Addition of vectors

vector addition
two or more vector quantities can be combined to produce a single resultant vector

There are many situations where more than one vector quantity is involved. When this is the case, we need rules to perform some form of arithmetic. We apply normal rules to scalar quantities – the rules for addition, subtraction, multiplication and division. In vector arithmetic, these rules must also take into account direction of the vector quantities. If you walk 3 m north and then 4 m south, your displacement is not 7 m.

Vector addition can be used to add two or more vector quantities to give a single resultant vector.

Case 1: same direction

Consider rowing a boat at 5 m s^{-1} E in water that is also moving east at 1 m s^{-1}. Your actual velocity is 6 m s^{-1} E, which is found by placing the two vector arrows head to tail. The **resultant** is a line drawn from the tail of the first arrow to the head of the second arrow (Figure 2).

resultant
the vector sum of two or more vectors

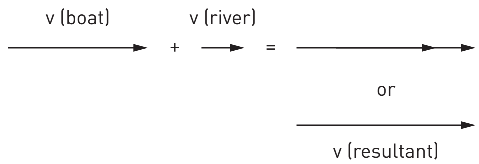

FIGURE 2 Adding vectors in the same direction

When adding vectors, the arrows should always be placed head to tail. The resultant will always start at the tail of the first arrow and end at the head of the second arrow.

Case 2: opposite directions

Consider the same boat being rowed against the current. In this case, the velocity of the river is 1 m s^{-1} W and is in the direction opposite to that of the boat and hence will slow the boat down.

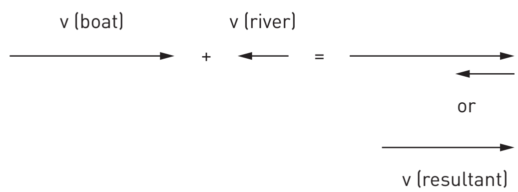

FIGURE 3 Adding vectors in opposite directions

The resultant velocity is 4 m s^{-1} E. When two vectors in the same line are added, the resultant has a direction the same as the larger vector.

Subtraction of vectors

In physics, we use subtraction to work out the change in some quantity. For example, if you heat up some water from 20°C to 30°C you would say there was a change in temperature of 10°C. But if you cool some water from 30°C to 20°C there would be a change of –10°C. We need to be very particular in the way we talk about 'change' in a measurement, particularly vectors. In physics, 'change' means subtraction:

Change in a measurement = final measurement – initial measurement

For temperature, this would read as: $\Delta T = T_{\text{final}} - T_{\text{initial}}$

This is simple for scalar quantities such as mass, temperature and bank balances. But in physics, it is also necessary to subtract vectors. You may have learnt that subtraction is the same as adding a negative. 10 – 6 is equivalent to 10 + (–6), and the answer is +4 either way. When subtracting vector B from vector A, the direction of vector B is changed to its opposite and then added to vector A (head to tail). Worked example 10.2 explains this further.

WORKED EXAMPLE 10.2

A ball strikes a wall at a velocity of −10 m s^{-1} (moving to the left) and rebounds at a velocity of +6 m s^{-1} (moving to the right). Calculate the change in velocity.

SOLUTION

Symbolically:

Initial velocity $\vec{v}_i = -10 \text{ m s}^{-1}$

Final velocity $\vec{v}_f = +6 \text{ m s}^{-1}$

Change in velocity = final velocity − initial velocity

$$\begin{aligned}\Delta\vec{v} &= \vec{v}_f - \vec{v}_i \\ &= +6 \text{ m s}^{-1} - (-10 \text{ m s}^{-1}) \\ &= +16 \text{ m s}^{-1}\end{aligned}$$

(The positive value means the change was directed to the right.)

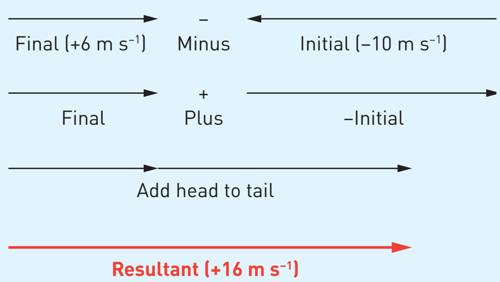

FIGURE 4 Showing how a subtraction is turned into an addition by reversing the initial velocity vector.

Graphically:

When subtracting graphically, we need to make it an addition because we have a head-to-tail rule for addition. So, we reverse the direction of the initial velocity vector and then just add it on, as in Figure 4.

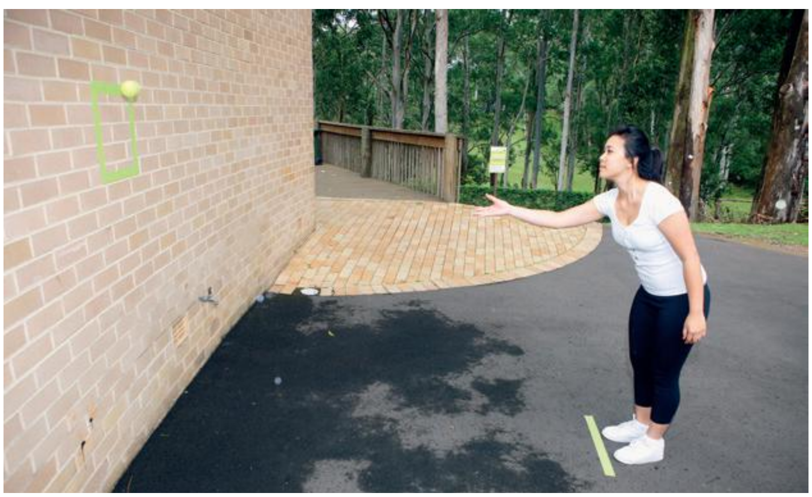

FIGURE 5 A ball strikes a wall and rebounds.

Multiplication of vectors

Multiplication of a vector by a scalar will change the magnitude of the vector but will leave its direction unchanged. If you are travelling in car A at a velocity of 10 m s^{-1} E, this can be represented by the vector $\vec{v}_A$ as shown in Figure 6 (left). If car B passes you at a velocity three times yours, we can represent this pictorially as $\vec{v}_B = 3 \times \vec{v}_A$, as shown in Figure 6 (right).

We could also represent this symbolically as $\vec{v}_A = +10 \text{ m s}^{-1}$; $\vec{v}_B = +30 \text{ m s}^{-1}$.

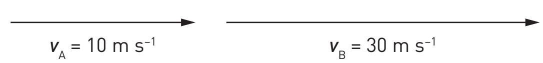

FIGURE 6 Multiplying a vector by 3 (graphically) means increasing its length by 3 times

MANDATORY PRACTICAL

10.2 Constructing and interpreting displacement-time and velocity-time graphs
Go to page 485 »

CHECK YOUR LEARNING 10.2

Describe and explain

1 **Describe** the two ways to represent a vector quantity. Provide an example of each.

2 **Calculate** the change in velocity for each of the cases in Table 1.

TABLE 1

	Initial velocity	Final velocity
a	20 m s^{-1} south	30 m s^{-1} north
b	50 m s^{-1} west	10 m s^{-1} east
c	25 m s^{-1} north	35 m s^{-1} south
d	50 m s^{-1} south	20 m s^{-1} north

3 **Calculate** the magnitude and direction of the resultant vector obtained by adding:

a displacements of 30 m east and 20 m east

b velocities of –6 m s^{-1} and +30 m s^{-1}.

4 **Calculate** (using a + or – symbol) the change in velocity for each of the cases in Table 2.

TABLE 2

	Initial velocity	Final velocity
a	20 m s^{-1} east	30 m s^{-1} west
b	50 m s^{-1} west	10 m s^{-1} east

5 **Symbolise** the magnitude and direction of the resultant vector obtained by adding:

a displacements of 30 m north and 20 m north

b velocities of 16 m s^{-1} north and 30 m s^{-1} south.

Apply, analyse and interpret

6 Two students leave home (A) and go to the shop (C), as shown in Figure 7. One student heads in a straight line for C, but the other student goes to C via B.

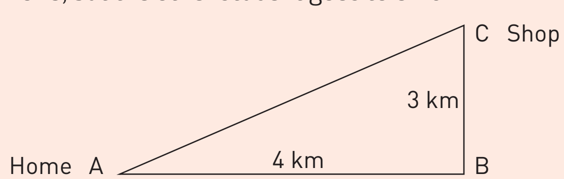

FIGURE 7 Students travelled from home (A) to the shop (C) either directly or via B.

a **Determine** the distance travelled by the person going directly to C.

b **Determine** the distance travelled by the person going to C via B.

c **Calculate** the displacement of the person at point B. ($\vec{s}_B$ = ?)

d **Calculate** the displacement at point C. ($\vec{s}_C$ = ?) Remember to include the direction by stating the value of the angle CAB.

7 A toy train is moving around a circular track of diameter 120 cm. Imagine it starts at the most northerly point (12 o'clock position). **Determine** the distance travelled and its displacement after:

a half a lap

b one full lap

c two laps

d quarter of a lap.

Investigate, evaluate and communicate

8 If you start in the middle of the oval and walk 100 m, consider where you could end up. **Evaluate** this with reference to the following questions.

a Can you cover a distance 100 m and end up where you started?

b Can you have a displacement of 100 m and end up there too?

c Can your 100 m distance travelled ever be greater than your displacement?

d Can your displacement ever be greater than your 100 m distance travelled?

Check your obook assess for these additional resources and more:

» Student book questions
Check your learning 10.2

» Mandatory practical
10.2 Constructing an interpreting displacement-time and velocity-time graphs

» Video
Displacement-time and velocity-time graphs

» Video worksheet
Displacement-time and velocity-time graphs

10.3 Speed and velocity

KEY IDEAS

In this section, you will learn about:

+ the concepts of velocity and speed.

The terms 'speed' and 'velocity' are often used as if they mean the same thing. When a newspaper report mentions a high-speed car chase, we know what is meant. But why are hunting rifles referred to as being high-velocity? Media reports may refer to high-velocity atomic particles, but also talk of a cyclone's wind speed. Such media reports often mean the same thing by speed and velocity. Why do you think they refer to some motions as speed and others as velocity?

Average speed

speed
the rate at which distance is covered

In physics, speed and velocity have slightly different meanings. **Speed** is a scalar quantity whereas velocity is a vector quantity. If it takes 2 h to drive the 120 km from Town A to Town B, then the average speed is 60 km h^{-1}. Speed is the rate at which distance is covered. The word 'rate' is a clue that something is being divided by time. Speed is always measured in terms of a unit of distance divided by a unit of time, such as metres per second.

Average speed is the rate of change of distance. It is found by dividing distance travelled by time taken.

$$\text{Average speed} = \frac{\text{total distance travelled}}{\text{time taken}}$$

$$v_{\text{av}} = \frac{s}{t}$$

Note that the symbols are not shown as vectors because speed, distance and time are all scalar quantities.

In the driving example, it doesn't mean that the car drove at 60 km h^{-1} all the way. Sometimes the car would have travelled at 100 km h^{-1} and at other times it would have been stationary. When the car's speedometer was reading 60 km h^{-1}, the car was actually travelling at a speed of 60 km h^{-1} for that moment. This is called its **instantaneous speed**.

instantaneous speed
the speed as measured over a very small period (an instant) of time

Average velocity

velocity
the rate of change of displacement of an object

When we talk of a car's speed as being 60 km h^{-1}, we have no idea about the direction it is travelling. Speed is a scalar quantity. **Velocity** can be defined as speed in a particular direction (such as 60 km h^{-1} north), but it is better to say that velocity is the rate of change of displacement.

$$\text{Average velocity} = \frac{\text{displacement}}{\text{time taken}}$$

$$\vec{v}_{\text{av}} = \frac{\vec{s}}{t}$$

Velocity is a vector quantity and the direction must be stated. In this book, a vector is represented by printing its symbol with an arrow overhead (such as $\vec{v}$ = 10 m s^{-1} N). You may sometimes see vectors in other sources shown using a bold font (such as $\boldsymbol{v}$ = 10 m s^{-1} N) or even an underline.

instantaneous velocity
the rate of change of displacement over a short instant of time

If the rate of change is measured at an instant in time, then this is an **instantaneous velocity**.

WORKED EXAMPLE 10.3

A person rides a bicycle 6.5 km east and then 2.5 km west, as shown in Figure 1. The trip takes 1.5 hours.

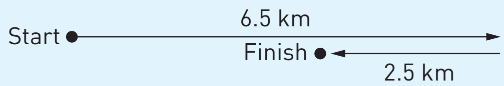

FIGURE 1 Diagram of a bicycle trip

Find the following:

a total distance travelled

b average speed

c displacement

d average velocity

SOLUTION

a Total distance = 6.5 km + 2.5 km

$= 9$ km

b Average speed $= \frac{\text{distance}}{\text{time}}$

$= \frac{9\text{ km}}{1.5\text{ h}}$

$= 6.0\ \text{km h}^{-1}$

c Displacement = +6.5 + (−2.5)

= +4 km (s = 4 km E)

d Average velocity $= \frac{\text{displacement}}{\text{time}}$

$= \frac{4\text{ km}}{1.5\text{ h}}$

$= 2.67\ \text{km h}^{-1}$ E

Study tip

An example of working out a car's average velocity can be found on your obook assess.

CHECK YOUR LEARNING 10.3

Describe and explain

1 An archer can fire an arrow at 390 m s^{-1}. **Calculate** the time an arrow would take to hit a target 100 m away.

Apply, analyse and interpret

2 In 1979 Sam Barrett is estimated to have reached a speed of 1190.4 km h^{-1}, in his rocket-engine three-wheeled car at Edwards Airforce Base. **Determine** the time it would have taken him to cover the 1.6 km test distance.

3 A student rides a bicycle to a shop by travelling 300 m north along a straight road and then by travelling west for another 400 m. If the trip takes 3 minutes, **determine**:

a the average speed

b the average velocity.

4 When driven by an experienced racing driver, a Ferrari Testarossa can cover 400 m from a standing start in 14.2 s. If it crosses the 400 m line at a speed of 203 km h^{-1}, **determine** its average speed.

5 **Analyse** the truthfulness of the following statement: 'When an object is moved, its displacement can be smaller than the distance travelled but the distance travelled can never be smaller than the displacement.'

Check your obook assess for these additional resources and more:

» Student book questions
Check your learning 10.3

» Increase your knowledge
Walking to running

» Increase your knowledge
Car's average velocity

» Weblink
Speed or velocity?

OA

10.4 Graphs of linear motion – constant speed

KEY IDEAS

In this section, you will learn about:

+ describing the motion of an object by interpreting a linear motion graph
+ calculating and interpreting the intercepts and gradients (slopes) and their uncertainties of displacement–time and velocity–time graphs
+ calculating and interpreting the areas under velocity–time and acceleration–time graphs
+ instantaneous velocity.

constant velocity motion where the magnitude of the speed and direction of the object is not changing; this includes an object at rest

The simplest kind of motion to study is an object moving with **constant velocity** and therefore zero acceleration. Examples include:

- a car being driven straight ahead at 60 km h^{-1}
- ball bearings being rolled on a very smooth horizontal surface
- a person jogging along a straight track
- water flowing in a straight pipe.

It is often useful to show data about motion in the form of a graph. The most basic form is a displacement vs time (s–t) graph. Not only does it show us how far an object has moved, but we can also use this graph to work out how fast an object was going. The second type of graph is velocity vs time (v–t). Both these types of graphs will be used to analyse motion that is at a constant velocity. Section 10.5 will look at accelerated motion graphs.

Displacement–time graphs

One of the simplest types of graphs is the displacement–time (s–t) graph, which just shows the displacement of an object as a function of time.

TABLE 1 Displacement and time measurements for a horse

Time elapsed (s)	0.0	1.0	2.0	3.0	4.0	5.0
Displacement (m)	0.0	10.0	20.0	30.0	40.0	50.0

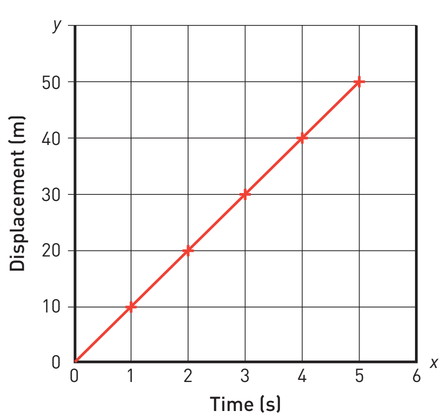

FIGURE 1 Horse's displacement as a function of time

For example, the position of a horse during a race was recorded at six different times (Table 1) and a displacement–time graph was plotted (Figure 1).

When drawing a displacement–time graph, it is usual to show the time elapsed on the horizontal axis and the displacement on the vertical axis, as in Figure 1.

The six points plotted on the graph are the six observations of the horse. When a line is drawn between these points, we are assuming the motion was uniform. This is called **interpolation** (Latin *inter* = 'between', *polire* = 'polish' – to 'polish up' data

interpolation a method of constructing new data points within the range of a set of known data points by supplying in-between points). When a line is extended past the first or last data points, this is called **extrapolation** (Latin *extra* = 'beyond').

extrapolation
a method of constructing new data points beyond the range of a set of known data points with the assumption that existing trends will continue

gradient
the slope of a graph

The horse's average velocity over the 5 seconds is calculated by dividing the displacement by the time taken. This is the same as calculating the gradient (slope) of the line.

The **gradient** of any line is given by change in y divided by the change in x ('rise over run'):

$$\text{Slope} = \frac{\Delta y}{\Delta x} = \frac{\text{rise}}{\text{run}} = \frac{y_2 - y_1}{x_2 - x_1}$$

For the horse:

$$\text{Gradient} = \frac{y_2 - y_1}{x_2 - x_1} = \frac{50 - 0}{5 - 0} = 10\ \text{m s}^{-1}$$

From a displacement–time graph, the gradient is given by:

$$v_{av} = \frac{\Delta y}{\Delta x} = \frac{\text{displacement}}{\text{time}}$$

The gradient of a displacement–time graph equals the velocity.

Therefore, for the horse:

$$v_{av} = \frac{\text{displacement}}{\text{time}} = \frac{100\ \text{m}}{10\ \text{s}} = 10\ \text{m s}^{-1}$$

WORKED EXAMPLE 10.4A

Figure 2 is the displacement–time graph of a sprinter who sprints 100 m in 10 s, rests for 20 s, and then runs back to the starting point in the next 30 s.

Using the graph, calculate the sprinter's average velocity:

a in the first 10 seconds

b from t = 30 s to t = 60 s.

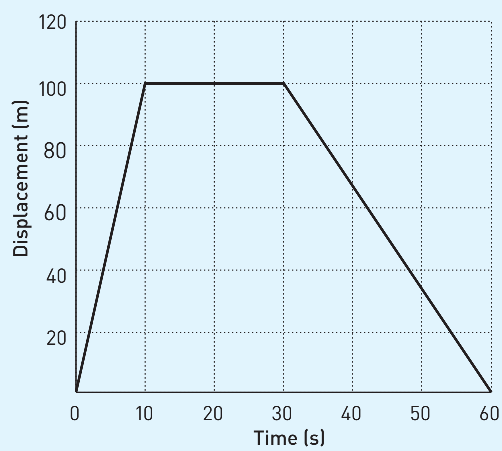

FIGURE 2 Displacement–time graph of sprinter

SOLUTION

a The sprinter's average velocity in the first 10 seconds is the gradient of the line over that time.

From the displacement–time graph, the gradient is given by:

$$v_{av} = \text{gradient} = \frac{\Delta y}{\Delta x} = \frac{\text{change in position}}{\text{time taken}} = \frac{100\ \text{m} - 0\ \text{m}}{10\ \text{s} - 0\ \text{s}} = 10\ \text{m s}^{-1}$$

The gradient of the line is constant for the first 10 seconds, indicating that the velocity was also constant.

b From t = 30 s to t = 60 s, the average velocity can be calculated:

$$v_{av} = \frac{0 - 100}{60 - 30} = -3.3\ \text{m s}^{-1}$$

Note that when the gradient of the line is positive, the velocity is in the positive direction. When the gradient is negative, the velocity is negative (which means the direction of motion has reversed).

Velocity-time graphs

The second type of graph useful for constant velocity motion is a velocity–time (v–t) graph. Consider the situation where an object is moving at constant speed (not accelerating). For example, the displacement–time graph of the horse from earlier is shown again below in Figure 3(a). Note that the horse increases its displacement by 10 metres for every 1 second elapsed. We calculated its average velocity to be 10 m s^{-1} and can plot this on a velocity–time graph as in Figure 3(b).

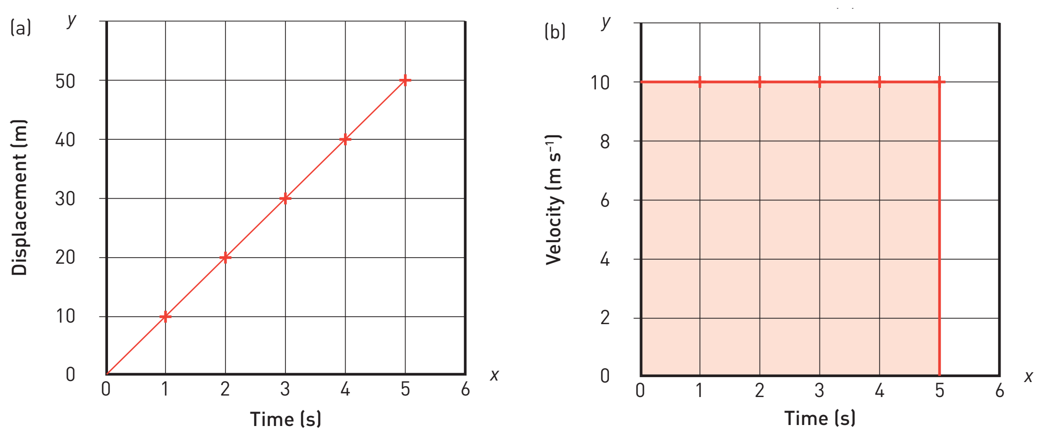

FIGURE 3 (a) Displacement–time graph of the horse; (b) Velocity–time graph of same data

Remember that the gradient of a displacement–time graph is the velocity. We can also calculate the displacement by rearranging the formula to give $s = vt$. The product of $v \times t$ is the area under the velocity–time curve (shown in orange). This area is 10 m s^{-1} × 5 s = 50 m, which is the final displacement of the horse after 5 s.

Summary

Relationships:

- Gradient of a displacement–time graph equals the velocity.
- Area under a velocity–time graph equals the displacement.

Graph shapes:

For an object travelling at constant speed, we can summarise graph shapes and their properties (Figure 4).

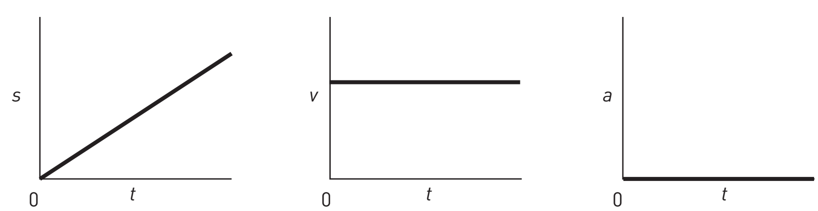

FIGURE 4 Graphs of constant velocity motion showing corresponding displacement–time, velocity–time and acceleration–time relationships

Non-constant speed and velocity

We have been looking at constant velocity motion but obviously objects do change their speed and velocity. You stop and start at traffic lights, you speed up to overtake another car, and you turn around to drive back home. We will now consider what the graphs would look like if a car did speed up.

A car's speedometer displays the instantaneous speed of the car. If it reads 60 km h^{-1}, then at the current speed you would cover 60 kilometres in 1 hour. However, you could be accelerating and the speedometer might be gradually changing from 50 km h^{-1} to 100 km h^{-1}. When it read 60 km h^{-1}, this was the car's instantaneous speed. If a direction is also specified, you would be talking about its instantaneous velocity. Worked example 10.4B shows how to calculate instantaneous velocity for non-linear graphs.

Study tip

The syllabus requires you to be able to determine instantaneous velocity for linear graphs. However, the procedure for calculating instantaneous velocity for non-linear graphs (non-constant speed) uses similar principles to linear graphs and is included below.

WORKED EXAMPLE 10.4B

Consider the case of a car accelerating away from traffic lights. The velocity is getting faster as time goes by, so the displacement–time graph is an exponential curve as shown in Figure 5. Calculate the instantaneous velocity at 2.5 s.

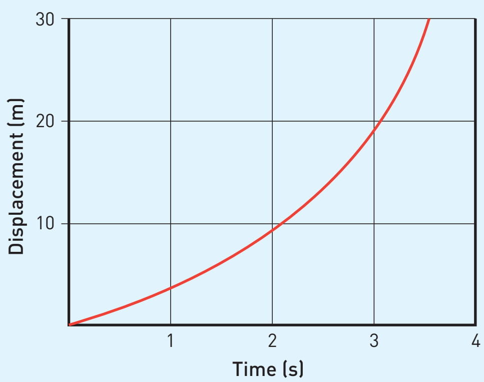

FIGURE 5 Displacement-time graph with a tangent drawn at 2.5 s.

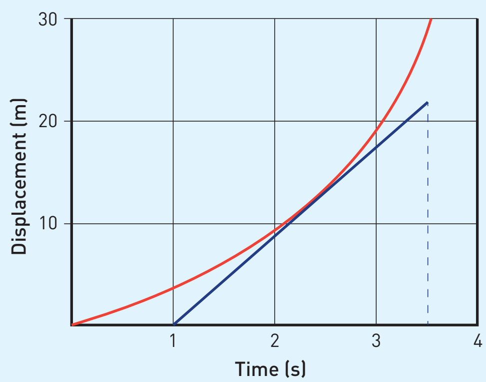

FIGURE 6 Displacement-time graph with an exponential curve

SOLUTION

To calculate the instantaneous velocity at 2.5 s in Figure 5, a tangent is drawn to the curve at the 2.5 s mark. The tangent is a line that just touches the curve at that point (Figure 6).

The gradient of the tangent can be calculated:

$$\text{Slope} = \frac{y_2 - y_1}{x_2 - x_1}$$

$$= \frac{20 - 0}{3.5 - 1}$$

$$= 8.0 \text{ m s}^{-1}$$

The instantaneous velocity at $t = 2.5$ s is 8 m s^{-1}.

CHECK YOUR LEARNING 10.4

Describe and explain

1 **Explain** how a student running around a school oval can be accelerating when they are travelling at constant speed.

2 For the graph of a roller-skater shown in Figure 7, **calculate** the skater's:

a average velocity for each of the five sections of the graph (A-E)

b average velocity for the whole journey

c average speed for the whole journey.

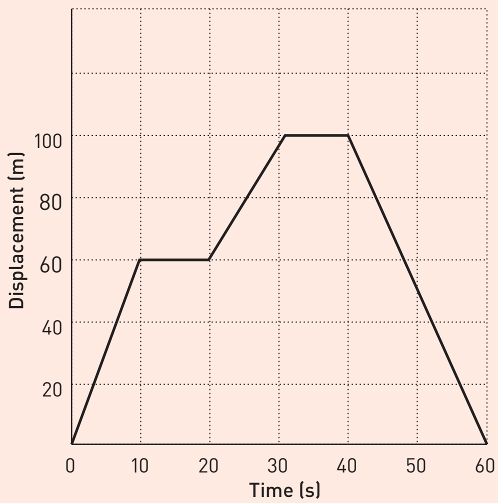

FIGURE 7 Displacement–time graph of a roller-skater

3 The graph in Figure 8 shows the displacement of an object rolling down a gradient. **Calculate** the instantaneous velocity at point A (t = 1.4 s). The tangent has been drawn in for you.

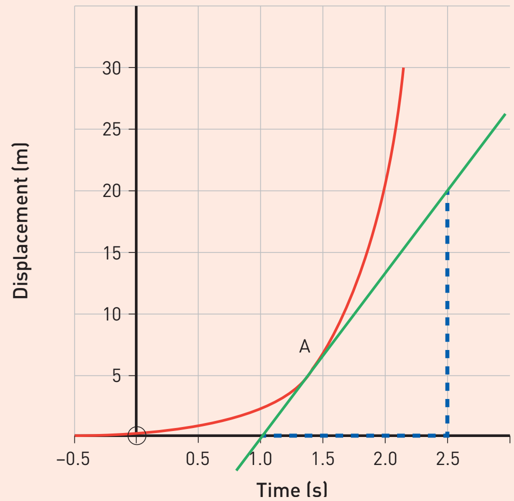

FIGURE 8 Displacement-time graph of an object rolling down an incline.

Apply, analyse and interpret

4 Table 2 records the motion of a dog chasing a ball.

TABLE 2

Time elapsed (s)	0	1	2	3	4	5	6	7	8	9
Displacement (m)	0	2	4	4	4	6	6	4	2	0

a **Sketch** a displacement–time graph of the motion and describe it in words.

b **Determine** when the dog was stationary.

c **Determine** when the dog's displacement was increasing.

d **Determine** when the dog was moving with the greatest speed.

5 **Clarify** what the gradient of a displacement–time graph represents.

Check your obook assess for these additional resources and more:

» **Student book questions**
Check your learning 10.4

» **Video**
Graphing

» **Video worksheet**
Graphing

» **Weblink**
Instantaneous speed

10.5 Graphs of uniformly accelerated motion

KEY IDEAS

In this section, you will learn about:

- describing the motion of an object by interpreting a linear motion graph
- calculating and interpreting the intercepts and gradients (slopes) and their uncertainties of displacement–time and velocity–time graphs
- calculating and interpreting the areas under velocity–time and acceleration–time graphs.

acceleration the rate of change of an object's velocity (symbol: *a*; SI unit symbol: m s^{-2})

uniform accelerated motion motion where the velocity is changing in magnitude or direction in a regular manner

Study tip

Remember that 'u' comes before 'v' in the alphabet, just as initial velocity (*u*) comes before final velocity (*v*).

The velocity of a car increases when it starts moving from rest and decreases when the brakes are applied and it slows down. Cars can thus accelerate (speed up) or decelerate (slow down). The rate at which the velocity changes is called its **acceleration**. In this section we will look at objects that undergo uniform acceleration, that is, where they keep getting faster or slower in a uniform way.

Uniformly accelerated motion is easy to find. Examples include:

- objects falling freely under gravity
- a car moving away uniformly from a traffic light
- a ball rolling down an incline.

Note that, in this section, vector arrows are not included over the symbols for displacement, velocity and acceleration because we are only working with the magnitudes of these vectors.

Acceleration

Acceleration is a vector quantity because velocity is a vector quantity.

$$\text{Acceleration} = \frac{\text{change in velocity}}{\text{time}}$$

$$= \frac{\Delta v}{t}$$

$$= \frac{\text{final velocity} - \text{initial velocity}}{t}$$

$$\vec{a} = \frac{\vec{v} - \vec{u}}{t}$$

We use the symbols u and v to represent initial and final velocities respectively.

Uniform acceleration graphs

WORKED EXAMPLE 10.5A

The measurements of a car taking off from the traffic lights are shown in Table 1.

TABLE 1

Time elapsed (s)	Displacement (m)	Velocity (m s^{-1})
0	0	0
1	1	2
2	4	4
3	9	6
4	16	8
5	25	10

Draw graphs of:

- displacement vs time
- velocity vs time
- acceleration vs time.

SOLUTION

The car's velocity is changing by 2 m s^{-1} every second. Its acceleration is said to be 2 m s^{-1} per second, or 2 m s^{-2}.

Note that the change of displacement is increasing for every second elapsed. In the 1st second, the displacement changes by 1 m, whereas in the 2nd second the displacement changes by 3 m. The data from Table 1 is plotted on the three graphs shown in Figure 1. You can see how graphs of uniformly accelerated motion are related.

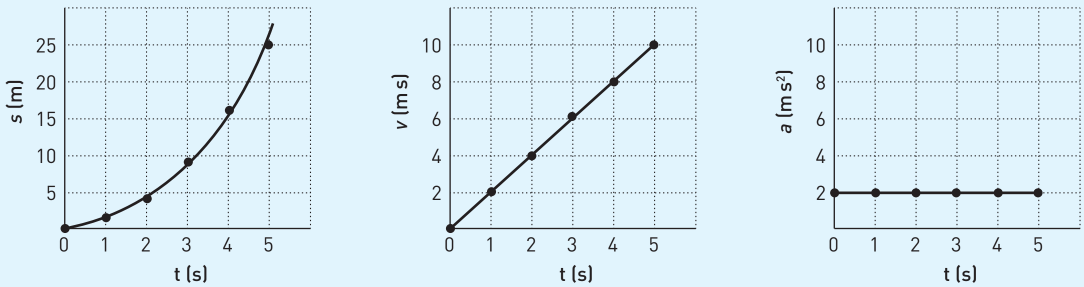

FIGURE 1 The graphs of the car's motion

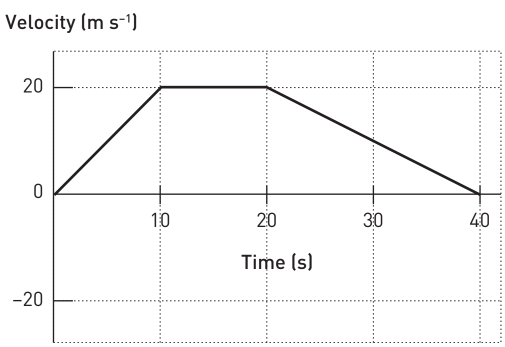

FIGURE 2 Velocity–time graph of a car

Velocity-time graphs

Velocity-time graphs are used to show the changes in velocity of an object with time. The graph in Figure 2 represents a car being accelerated from rest to 20 m s^{-1} in 10 s and then being held at that speed for 10 s before the driver slows down to a stop over the next 20 s.

A straight line sloping upward indicates constant acceleration, whereas a straight line sloping down indicates deceleration. A horizontal line indicates zero acceleration, which is constant velocity. The formula for acceleration $a = \frac{v - u}{t}$ is equivalent to $\frac{\Delta y}{\Delta x}$, so acceleration is equal to the gradient of a velocity–time graph.

The displacement can be calculated by finding the area under the line. This will be shown in the worked example.

WORKED EXAMPLE 10.5B

Use the graph of the car's motion in Figure 2 to answer the following questions.

a Calculate the acceleration of the car at:

i 5 s

ii 15 s

iii 30 s.

b Calculate the displacement after 40 s.

c Calculate the average velocity.

d Sketch an acceleration–time graph.

SOLUTION

a **i** The acceleration at 5 s is equal to the gradient at 5 s.

$a = \text{gradient} = \frac{20 - 0}{10} = 2 \text{ m s}^{-1}$

ii Gradient equals zero, therefore acceleration is zero.

iii $a = \text{gradient} = \frac{0 - 20}{40 - 20} = -1 \text{ m s}^{-1}$

b The displacement is the area under the curve.

Total area = area A + area B + area C

$$\text{Total area} = \frac{10 \times 20}{2} + 10 \times 20 + \frac{20 \times 20}{2}$$
$$= 100 + 200 + 200$$
$$= 500 \text{ m}$$
$$s = 500 \text{ m (or } 5 \times 10^2 \text{ m)}$$

c $\text{Average velocity} = \frac{\text{displacement}}{\text{time}}$

$$v_{av} = \frac{s}{t} = \frac{500}{40} = 12.5 \text{ m s}^{-1}$$

d Acceleration–time graph. Data from part (a) showed that acceleration is:

i 2 m s^{-2},
ii 0 m s^{-2},
iii -1 m s^{-2}

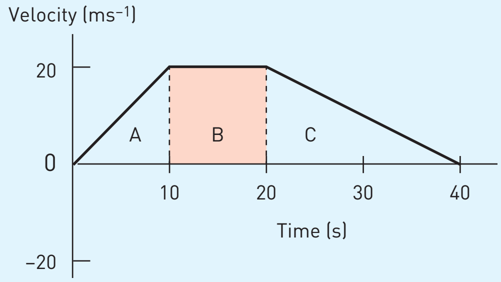

FIGURE 3 Displacement is the area under the curve of a velocity–time graph.

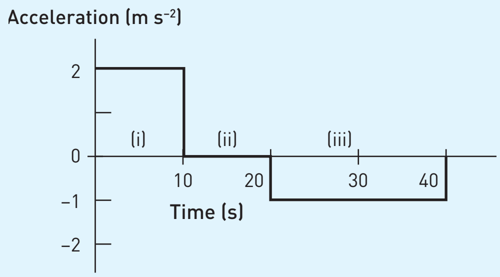

FIGURE 4 Acceleration–time graph

Negative velocities

For cases where the velocity becomes negative, the area beneath the *x*-axis is also negative and this must be taken into account when calculating displacement.

For example, imagine the motion of a bungee jumper jumping off a tower (Figure 5).

The displacement after 50 s is the area under the curve for the 50 seconds.

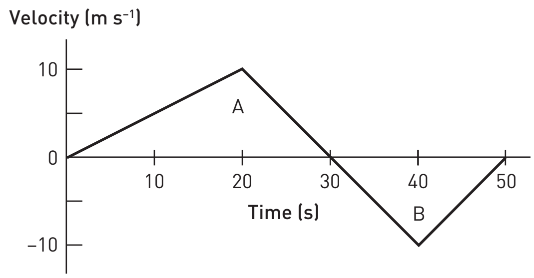

FIGURE 5 The motion of a bungee jumper after jumping off a tower

Area under curve = area A + area B

$$= \frac{\text{base of A} \times \text{height of A}}{2} + \frac{\text{base of B} \times \text{height of B}}{2}$$
$$= \frac{30 \times 10}{2} + \frac{20 \times -10}{2} \text{ (note that the height of triangle B is } -10 \text{ m s}^{-1})$$
$$= 150 + (-100)$$
$$= 50 \text{ m}$$

However, the distance travelled after 50 s is not a vector quantity and the area underneath the *x*-axis for triangle B is not considered as negative. The distance travelled is 250 m (150 m down plus 100 m back up).

$$\text{Area under curve} = \frac{\text{base of A} \times \text{height of A}}{2} + \frac{\text{base of B} \times \text{height of B}}{2}$$
$$= \frac{30 \times 10}{2} + \frac{20 \times 10}{2}$$
$$= 150 + 100$$
$$= 250 \text{ m}$$

Summary

Relationships:

- Gradient of a velocity–time graph equals the acceleration.
- Area under a velocity–time graph equals the displacement.

Graph shapes:

For an object travelling with uniformly accelerated motion, we can summarise graph shapes and their properties (Figure 6).

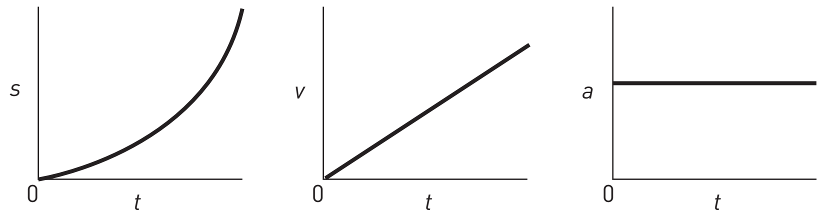

FIGURE 6 Motion graphs showing corresponding displacement–time, velocity–time and acceleration–time relations for situations of uniform acceleration.

CHALLENGE 10.5

Train times

The 8.00 a.m. express train from Cleveland to Brisbane arrives at 9.00 a.m., and the 8.30 a.m. from Brisbane to Cleveland arrives at 9.30 a.m. Assuming both trains travel at constant speed, at what time should they pass each other?

FIGURE 7 What time will the trains travelling in opposite directions pass each other?

CHECK YOUR LEARNING 10.5

Describe and explain

1 **Recall** what each of the following represents:
  a gradient of a *s*–*t* graph
  b gradient of a *v*–*t* graph
  c area under a *v*–*t* graph.

2 Figure 8 shows the motion of a bungee jumper.

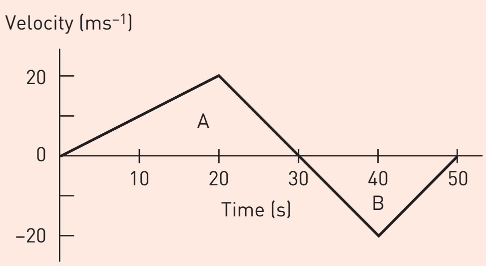

FIGURE 8 Motion of a bungee jumper

  a i **Calculate** the bungee jumper's displacement and distance travelled after 40 s.
    ii **Calculate** the bungee jumper's acceleration at 10 s, 30 s and 45 s.
    iii **Sketch** an acceleration–time graph.
  b **Identify** when the bungee jumper was stationary.
  c **Identify** when the bungee jumper's acceleration was constant but not zero.
  d **Identify** when the bungee jumper's velocity was constant but not zero.

3 The graph shown in Figure 9 illustrates the motion of a skateboard rider.

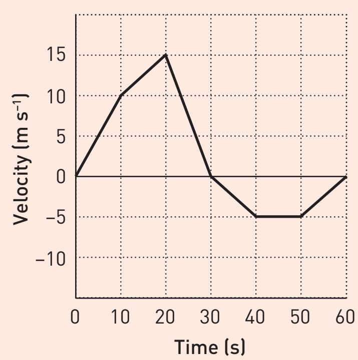

FIGURE 9 Motion of a skateboard rider

a **Calculate** the skater's displacement after 1 minute.

b **Calculate** how far the skater travelled in the minute.

c At what stage was the magnitude of the skater's acceleration the greatest?

d When was the skater stationary?

e When was the skater's acceleration negative and constant?

f When was the skater's velocity constant but not zero?

4 A runner is attempting to improve her stamina. She runs along a straight track and her motion is shown on the graph in Figure 10.

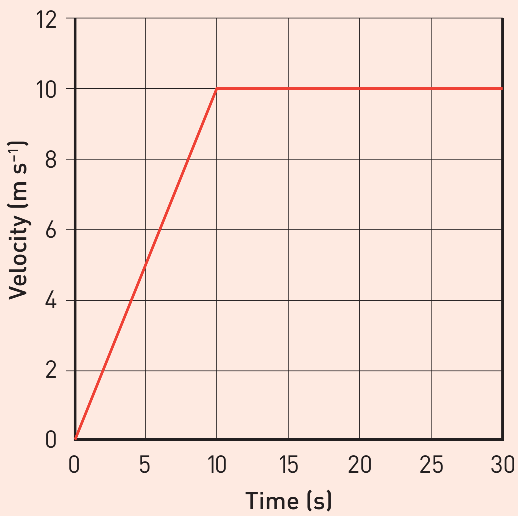

FIGURE 10 Motion graph of a runner

a **Calculate** the distance she covered after 20 s.

b **Calculate** her instantaneous speed at 5 s.

c **Calculate** her average speed for the whole 30 s.

5 You may have heard the story about a hare (rabbit) who ridicules a slow-moving tortoise. Tired of the hare's boastful behaviour, the tortoise challenges the hare to a race. The hare soon leaves the tortoise behind and, confident of winning, takes a nap midway through the race. The hare awakes to find that the tortoise, crawling slowly but steadily, has arrived at the finish line first.

a **Sketch** a displacement–time graph to show how the tortoise won.

b **Sketch** a velocity–time graph to show how the tortoise won.

c **Sketch** an acceleration-time graph of the same motion.

Apply, analyse and interpret

6 Table 2 shows the data of a ball rolling down an incline.

TABLE 2

Time elapsed (s)	Displacement (m)	Velocity ($m\ s^{-1}$)
0	0	0
1	3	6
2	12	12
3	27	18
4	48	24
5	75	30

a **Sketch** an *s*–*t* graph and a *v*–*t* graph of the data.

b By inspection of the data, **determine** the acceleration of the rolling ball.

c **Determine** if this is an example of uniformly accelerated motion. Explain by reference to the data.

Check your obook assess for these additional resources and more:

» Student book questions
Check your learning 10.5

» Challenge
10.5 Train times

» Video
Velocity-time graphs

» Video worksheet
Velocity-time graphs

10.6 Equations of motion

KEY IDEAS

In this section, you will learn about:

+ developing formulas of motion
+ solving problems involving the equations of uniformly accelerated motion in one dimension.

Graphs are one way of analysing motion, but we can also do the same using algebra. In this section, we will see how the equations used so far can be combined to provide other useful ways of calculating and describing the motion of objects.

Development of motion formulas

The definitions of velocity and acceleration can be turned into formulas for use in solving problems algebraically. Many of the formulas can also be rearranged or combined to produce new formulas. Several examples are presented here along with worked solutions and practice problems. Teachers commonly call these formulas the '*suvat*' formulas (Table 1).

Note that the vector sign from the variables s, u, v, a has been omitted. The sign convention for positive motion and the oppositely directed negative motion has been used.

TABLE 1 The '*suvat*' formulas

s	*u*	*v*	*a*	*t*
displacement	initial velocity	final velocity	acceleration	time

1 Rearrangement

We can start with the definition of acceleration as the rate of change of velocity and rearrange it:

$$\text{Acceleration} = \frac{\text{change in velocity}}{\text{time}}$$

$$= \frac{\text{final velocity} - \text{initial velocity}}{\text{time}}$$

$$a = \frac{v - u}{t}$$

$$v = u + at$$

$$v = u + at \quad \text{(Equation 1)}$$

2 Substitution

Two separate formulas for average velocity can be combined:

$$\text{Average velocity} = \frac{s}{t}\text{, which also equals } \frac{u + v}{2}.$$

$$\frac{u + v}{2} = \frac{s}{t}$$

$$s = \frac{(u + v)\,t}{2}$$

$$s = \frac{(u + v)\,t}{2} \quad \text{(Equation 2)}$$

We can then substitute equation (1) into (2):

$$s = \frac{(u + (u + at))\,t}{2}$$

$$= ut + \frac{1}{2}at^2$$

$$s = ut + \frac{1}{2}at^2 \quad \text{(Equation 3)}$$

3 Other substitution

We can further substitute one equation into another:

From equation (1) we get $t = \frac{v-u}{a}$. Substituting this into equation (2), we get:

$$s = \frac{u+v}{2} \times \frac{v-u}{a}$$
$$2as = (u+v)(v-u)$$
$$= v^2 - u^2$$
$$v^2 = u^2 + 2as$$
$$v^2 = u^2 + 2as \quad \text{(Equation 4)}$$

Study tip

A summary of solving problems of uniformly accelerated motion can be found on your obook assess.

WORKED EXAMPLE 10.6

1 A car starts from rest and reaches a velocity of 60 km h^{-1} (16.67 m s^{-1}) in 8 seconds. Assuming the acceleration to be constant, calculate:

a the acceleration in this time interval

b the displacement in this time interval.

2 A train starting from rest travels 30 m in 6 s. Find:

a its acceleration after 6 s

b its velocity after 6 s.

SOLUTION

1 $u = 0$; $v = 16.67$ m s^{-1}; $t = 8$ s; $a = ?$; $s = ?$

a $a = \frac{v-u}{t} = \frac{16.67-0}{8} = 2.084$ m s^{-2}

b $s = ut + \frac{1}{2}at^2 = 0 + \frac{1}{2} \times 2.084 \times 8^2 = 66.69$ m

2 $u = 0$; $s = 30$ m; $t = 6$ s; $a = ?$; $v = ?$

a $s = ut + \frac{1}{2}at^2$

$30 = 0 + \frac{1}{2} \times a \times 6^2$

$30 = 18a$

$a = 1.7$ m s^{-2}

b $v = u + at$

$= 0 + 1.7 \times 6$

$= 10$ m s^{-1}

CHALLENGE 10.6

Army troop ride

A column of troops 3 km long is marching along a road. An officer rides from the rear to the head of the column and back to the rear of the column of troops. He reaches the rear of the column just as an advance of 4 km has been made from where he first left. How far did he ride?

FIGURE 1 How far did the officer ride along the column of troops?

CHECK YOUR LEARNING 10.6

Describe and explain

1 **Identify** what formula links the magnitude symbols *s, v, t* and *a*.

2 One of the '*suvat*' formulas has been rearranged to give $v^2 - u^2$ =? **Identify** the original formula and complete the one presented here.

3 Rearrange $v = u + at$ so that *t* is the subject of the equation t = ?

4 **Explain** what a negative value for acceleration means in terms of motion of an object.

5 A man goes from A to B at 30 km h^{-1}. **Calculate** how fast he must return to average 40 km h^{-1} for the whole trip.

6 A bus travelling in a straight line accelerates from 60 km h^{-1} to 100 km h^{-1} in 1 minute. **Calculate** the acceleration in m s^{-2}.

7 A road-tested acceleration for a standard production car of 0 to 96.5 km h^{-1} (26.8 m s^{-1}) in 3.98 s was reported for a Ferrari F40 driven by Mark Hales in 1989. **Calculate** the acceleration of the car.

8 The head of a rattlesnake can accelerate at 50 m s^{-2} when striking a victim. If a car could match this acceleration, **calculate** how many seconds it would take for the car to reach a speed of 27 m s^{-1} (100 km h^{-1}) from rest.

9 A car moving at 30 m s^{-1} decelerates at a uniform rate of 1.5 m s^{-2}. **Calculate** how many seconds it will take the car to stop and how far will it travel in this time.

Apply, analyse and interpret

10 Copy and complete Table 2 to **determine** equations of motion. Remember that change in velocity $\Delta v = v - u$.

TABLE 2

	v (m s^{-1})	*u* (m s^{-1})	Δv (m s^{-1})	*t* (s)	*a* (m s^{-2})
a	18	10		2.0	
b	42		4		4.0

11 Copy and complete Table 3 to **determine** equations of motion.

TABLE 3

	s (m)	*u* (m s^{-1})	*v* (m s^{-1})	*a* (m s^{-2})	*t* (s)
a		0		2.5	3
b	100	0			2.4
c		10	25	2	

12 A cyclist starts from rest and attains a velocity of 21 m s^{-1} in 3.5 seconds. **Determine**:

a the acceleration (assumed constant).

b the displacement.

13 The click beetle (*Athous haemorrhoidalis*) experiences an acceleration of 24 000 m s^{-2} over a distance of 5 mm when it jack-knifes into the air to avoid predators. **Determine** the time duration over which this acceleration occurs.

14 Two cars accelerate at 2 m s^{-2} for 10 seconds. **Deduce** whether they will both cover the same distance, and support your reasoning with data.

Check your obook assess for these additional resources and more:

» **Student book questions**
Check your learning 10.6

» **Challenge**
10.6 Army troop ride

» **Increase your knowledge**
Uniformly accelerated motion

» **Weblink**
Motion

10.7 Acceleration due to gravity

KEY IDEAS

In this section, you will learn about:

- acceleration due to gravity
- free-fall motion.

gravity
the force of attraction between all masses in the universe

free-fall motion
any motion of a body where gravity is the only force acting upon it

One of the most common examples of uniformly accelerated motion in a straight line is an object that falls freely due to **gravity**. Until Galileo (1564–1642), people thought that heavy objects fell faster than light objects. They saw no need for experiments that may have confirmed or refuted these beliefs. They relied on the theories of Aristotle, who believed that objects fell at speeds that depended on their weight. Galileo performed some of the earliest experiments that showed that both heavy and light objects in the absence of air and other resistance fell with constant acceleration. Thus, two objects of different masses, dropped from the same height at the same time, should strike the ground simultaneously.

Motion due to gravity can take two main forms: vertical motion and projectile motion. Vertical motion involves an object moving in one dimension only (up and down). Projectile motion involves an object moving horizontally as well as vertically, such as a stone thrown off a cliff. This chapter deals only with vertical motion. In Unit 3 projectile motion, which involves both vertical and horizontal motion, is dealt with in detail.

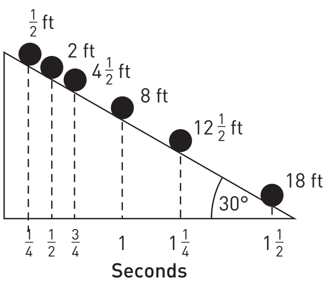

FIGURE 1 Galileo's data from his inclined plane experiments

Types of free-fall motion

Vertical **free-fall motion** can be grouped into two classes:

1. The object is being dropped or thrown down.
2. The object is being thrown upward.

When dealing with calculations involving acceleration due to gravity, we need to assign a positive and negative direction of motion. Unless otherwise stated, we will use the convention of upward as positive and downward as negative (this is the most common).

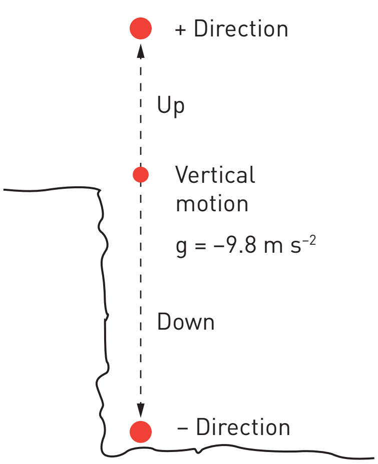

FIGURE 2 The most common convention is upward as positive and downward as negative.

Acceleration due to gravity

Acceleration due to gravity near Earth's surface is constant at 9.8 m s^{-2}. The net force on a free-falling object will be downwards, which is in the negative direction. Hence, the acceleration due to gravity is negative, $a = -9.8$ m s^{-2}. This means an object will increase its velocity in the negative direction by 9.8 m s^{-1} every second, or by 9.8 metres per second per second.

Students often think a negative acceleration means deceleration or slowing down, but this is not always so. If an object is moving in the negative direction (down) and has negative acceleration such as on Earth with a free-fall acceleration of −9.8 m s^{-2}, then the object will get faster in that negative direction. If the object is moving in the positive direction (upward) and has a negative acceleration,

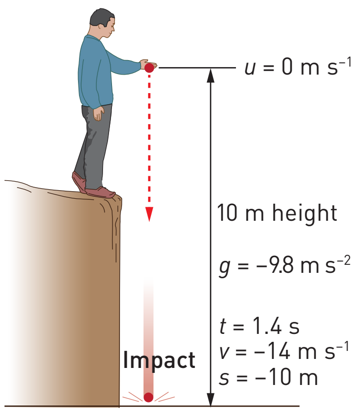

FIGURE 3 A man drops a ball off a cliff from a 10 m height. The displacement at the base of the cliff is −10 m. The impact velocity is also negative (−14 m s^{-1}).

then the object will slow down in that positive direction. It seems confusing at first, but practice with the formulas will help you come to terms with this.

Dropping or throwing an object down

Dropping or throwing an object down typically involves dropping it from a high place such as a cliff or throwing it vertically downward. In both cases the velocity increases in the negative direction. The only difference is the initial velocity. When an object is dropped, the initial velocity (u) is zero. When an object is thrown down, the velocity begins at a negative value (because negative is down). Either way, the velocity increases in the negative direction.

Study tip

Some further worked examples involving types of free-fall motion can be found on your obook assess.

WORKED EXAMPLE 10.7A

A spanner is dropped from a sixth-floor window and takes 2.2 s to hit the ground. Calculate:

a the height from which it was dropped

b its impact velocity.

SOLUTION

$u = 0$ m s^{-1}; $a = -9.8$ m s^{-2}; $t = 2.2$ s; $s = ?$; $v = ?$

a $s = ut + \frac{1}{2}at^2$

$= 0 + \frac{1}{2} \times -9.8 \times (2.2)^2$

$= -23.7$ m

Answer: The spanner was dropped from a height of 23.7 m.

Note that the answer is a displacement (s) of −23.7 m. This means it was 23.7 m in the negative direction from where it started. The question asked for the height, and a final displacement of −23.7 m means it started off at a height of 23.7 m, so this is the answer.

b $v = u + at$

$= 0 + -9.8 \times 2.2$ vertically down

$= -21.56$ m s^{-1}

$= -22$ m s^{-1}

The negative means it has a speed of −22 m s^{-1} or 22 m s^{-1} in the negative direction. As velocity is a vector quantity, you must state the direction, either by including the negative sign or using the words 'vertically down'.

Throwing an object upward

Trajectory of an object thrown vertically

When a ball is thrown vertically upwards, it starts at a high initial velocity in the positive direction, gradually slows to a halt at the top of its flight and then gradually increases velocity in the negative direction until it returns to the ground.

Figure 4 shows the flight of a ball thrown vertically upwards. Note: although its downward path is exactly the same as the upward path, it is drawn slightly to the right for clarity.

Notice that:

- velocity equals zero at the top of flight
- time of flight up equals time down
- acceleration is constant at -9.8 m s^{-2}, even at the top of flight when velocity is zero
- final speed equals initial speed
- final velocity equals the negative of the initial velocity
- air resistance is negligible and can be ignored for our purposes.

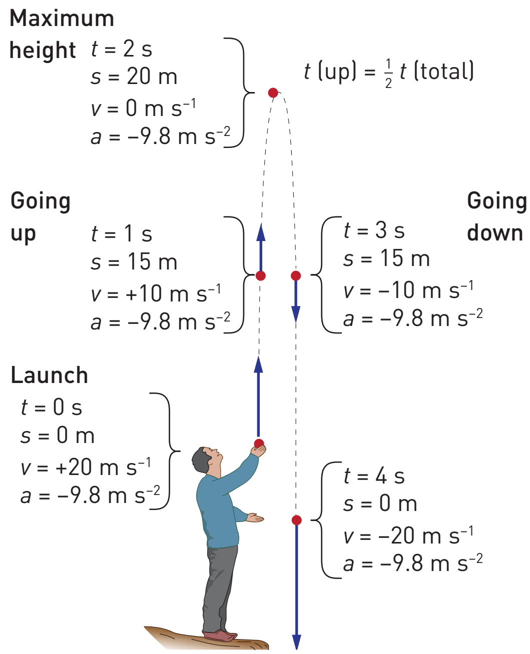

FIGURE 4 Flight of a ball thrown vertically upward

WORKED EXAMPLE 10.7B

A ball is thrown vertically upwards at 20 m s^{-1}. Ignoring air resistance and taking $g = -9.8$ m s^{-2}, calculate:

a how high the ball goes

b the time taken to reach this height

c the time taken to reach the ground from the highest point

d the final velocity

e total time of flight.

SOLUTION

$u = +20$ m s^{-1}; $a = -9.8$ m s^{-2}; $s = ?$ m.

a At the top of flight, $v = 0$ m s^{-1}

$$v^2 = u^2 + 2as$$
$$0 = (+20)^2 + 2 \times -9.8 \times s$$
$$19.6 \times s = 400$$

$s = 20.4$ m (i.e. 20.4 m up in the air). Note that it is a positive value.

b $v = u + at$

$0 = +20 + -9.8t$

$t = 2.04$ s

c The ground is 20.4 m in the negative direction from the top of flight. Hence, $s = -20.4$ m.

$$s = ut + \frac{1}{2}at^2$$
$$-20.4 = 0 + -4.9t^2$$
$$t = 2.04 \text{ s}$$

d $v = u + at$

$= 0 + -9.8 \times 2.04$

$= -20$ m s^{-1}

e Time up = 2.04 s; time down = 2.04 s. Hence, total time of flight is 4.08 s. Using the equations of motion, it can be shown that when the displacement is zero, the time for this to occur is 0 s (the start) and 4.08 s (the finish):

$$s = ut + \frac{1}{2}at^2$$
$$0 = 20 \times t + -4.9t^2$$
$$4.9t^2 = 20t$$
$$t = \frac{20}{4.9}$$
$$= 4.08 \text{ s}$$

Graphs of free-fall motion

The two most common types of free-fall motion (dropped and thrown upwards) can be examined graphically.

Dropped down

Figure 5 shows the relationship between an acceleration–time graph and the corresponding velocity–time graph for an object dropped off a cliff. The downward direction is negative as usual.

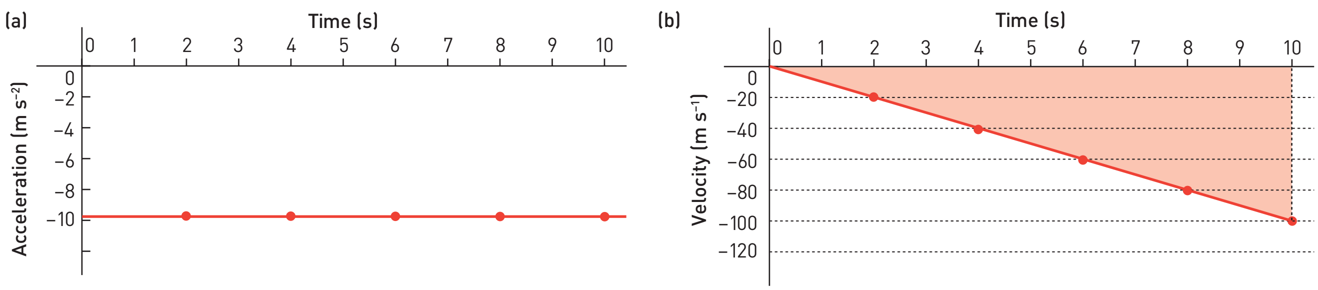

FIGURE 5 (a) An acceleration–time graph; (b) a velocity–time graph (The shaded area indicates the displacement.)

Thrown upwards

Figure 6 shows the graphs of motion of an object (such as a ball) thrown upwards into the air and allowed to return to its starting place. Note that the acceleration is constant, even at the top of flight when the ball is stationary. Again, down is negative.

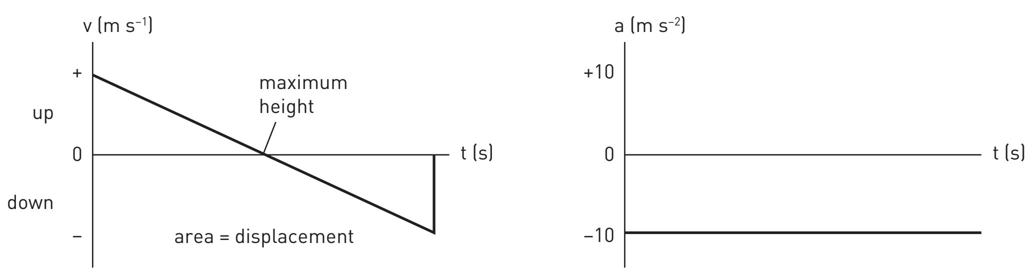

FIGURE 6 Graphs of the motion of an object thrown vertically upwards

CHECK YOUR LEARNING 10.7

Describe and explain

1 **Explain** why the acceleration of an object thrown upwards is not zero at the top of its flight.

2 **Explain** why the velocity of an object at maximum height is zero.

3 A rock is dropped off a cliff and it takes 4.0 s to reach the base below. **Calculate** how high the cliff is.

4 A rock is launched vertically upward from the ground at a starting speed of 35 m s^{-1}.

  a **Calculate** the maximum height reached.

  b **Calculate** the time taken to reach this maximum height.

  c **Calculate** the time taken to fall from maximum height back to the ground again.

5 A person is in a hot-air balloon moving vertically upward at a constant speed of 4.9 m s^{-1}. They drop a sandbag when the balloon is at an elevation of 98 m.

  a **Calculate** the velocity of the sandbag on impact.

  b **Calculate** the time it will take until the sandbag hits the ground.

Apply, analyse and interpret

6 A pot-plant falls 25.0 m from rest to the ground below.

  a **Determine** its impact velocity.

  b **Determine** the time it took to fall.

Investigate, evaluate and communicate

7 **Propose** a response to the statement: 'Acceleration due to gravity is +9.8 m s^{-2} on the other side of Earth'.

8 You are presented with this information: a startled armadillo leaps upward and rises 54.4 cm in the first 0.20 s and keeps rising.

  a **Calculate** the armadillo's initial speed.

  b **Calculate** its speed at 54.4 cm.

  c **Predict** how much higher it goes.

  d **Evaluate** this statement: 'The armadillo's maximum acceleration was at push-off from rest.'

9 Driving along a country road, a man and a woman have a dispute about reading the map. The woman gets out of the car, stands on the edge of a cliff, and throws her wedding ring vertically upwards. As the ring passes her on the way down 3.4 seconds later, she drops her other ring – an engagement ring – off the cliff.

  a **Calculate** how many seconds apart the two rings strike the rocks 50 m below. Assume air resistance is negligible.

  b From the time the rings leave the woman's hand until they each reach the ground, **discuss** what acceleration/s they experience.

Check your obook assess for these additional resources and more:

» **Student book questions**
Check your learning 10.7

» **Increase your knowledge**
Worked examples involving free-fall motion

» **Video**
LoggerPro analysis Nerf Gun

» **Video tutorial**
LoggerPro analysis Nerf Gun

CHAPTER 10

Review

Summary

10.1
- In the coordinate system for the vertical direction, upward is positive and downward is negative.
- In the coordinate system for the horizontal direction, right is positive and left is negative.
- Motion can be represented by a scalar quantity that has a magnitude only, or by a vector that has both magnitude and direction.
- Vectors can be represented pictorially by directed line segments (arrows), or symbolically by the positive or negative sign.
- To add pictorial vectors they are placed head to tail and the resultant is from the tail of the first to the head of the final vector.
- To subtract a pictorial vector, its direction is reversed to make it an addition.

10.2
- Displacement is the change of position in a particular direction.

10.3
- Average speed of an object is the distance covered divided by the time taken.
- Average velocity is the displacement divided by the time taken.
- Instantaneous velocity is the rate of change of displacement over a short instant of time.

10.4
- Acceleration of an object is its change in velocity divided by the time taken for the change.
- Gradient of a displacement–time graph is the instantaneous velocity.
- Area under a velocity–time graph indicates the displacement.
- Gradient of a velocity–time graph indicates the acceleration.
- Objects that free-fall under gravity on Earth have a constant acceleration of 9.8 m s^{-2} in the negative (downwards) direction.

10.5
- The gradient of a displacement-time graph represents the instantaneous velocity.
- The area under a velocity-time graph represents the displacement.
- The gradient of a velocity-time graph represents the acceleration.

10.6
- The 'suvat' formulas allow calculation of displacement, initial and final velocity, acceleration and time elapsed for a particular motion.

10.7
- For free-fall motion on the surface of the Earth, the acceleration due to gravity is –9.8 m s^{-2} (directed downwards) at all stages of the motion.

Key terms

- acceleration
- constant velocity
- directed line segment
- displacement
- distance
- extrapolation
- free-fall motion
- gradient
- gravity
- instantaneous speed
- instantaneous velocity
- interpolation
- resultant
- scalar quantities
- speed
- uniformly accelerated motion
- vector addition
- vector quantities
- velocity

Key formulas

Motion formula (velocity)	$v = u + at$
Motion formula (displacement)	$s = ut + \frac{1}{2}at^2$
Motion formula	$v^2 = u^2 + 2as$
Average velocity	$\vec{v}_{av} = \frac{\vec{s}}{t}$

Revision questions

The relative difficulty of these questions is indicated by the number of stars beside each question number: ★ = low; ★★ = medium; ★★★ = high.

Multiple-choice

1 Figure 1 is a speed versus time graph for an object moving in a straight line.

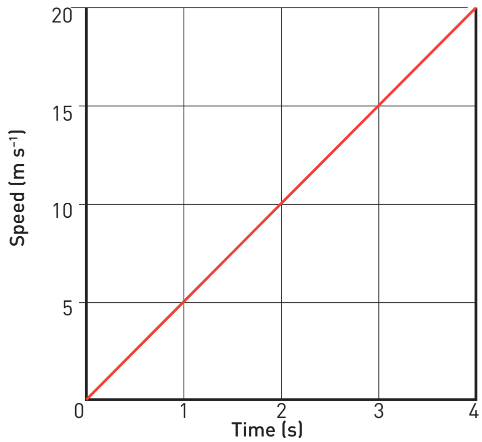

FIGURE 1 Speed–time graph for an object moving in a straight line

The distance travelled by the object during the first 4 seconds is:

A 80 m **B** 40 m **C** 20 m **D** 5 m

2 Which of the following quantities can be determined from a speed–time graph of a particle travelling in a straight line?

A only the magnitude of the acceleration at a given instant

B both the velocity and the acceleration at a given instant

C only the distance travelled in a given time

D both the distance travelled in a given time and the magnitude of the acceleration at a given instant

3 Samantha walks along a horizontal path in the direction shown in Figure 2. The curved part of the path is a semi-circle.

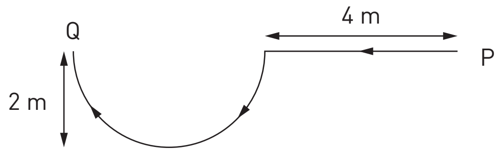

FIGURE 2 Diagram of Samantha's walk

The magnitude of her displacement from point P to point Q is approximately:

A 4 m **B** 6 m **C** 8 m **D** 10 m

4 A ball is thrown upwards and caught at the same height as it comes back down. In the absence of air resistance, the speed of the ball just before it is caught would be:

A less than the speed it had when thrown upwards

B more than the speed it had when thrown upwards

C the same speed it had when thrown upwards

D 0 m s^{-1}

5 A car accelerates at 2 m s^{-2}. Assuming the car started from rest, how much time will it need to accelerate to a speed of 20 m s^{-1}?

A 2 s **B** 10 s **C** 20 s **D** 40 s

Short answer

Describe and explain

★ 6 **Define** acceleration, change in speed, change in velocity, displacement, distance, linear motion, speed, vector and velocity.

★ 7 The best time by an Australian in the 42.2 km marathon is 2 h 7 min 51 s. **Calculate**:

a the average speed

b the time it would take a 100 m sprint champion if they ran the 42.2 km distance at 10.15 m s^{-1}.

★ 8 A person runs in a straight line 84 m south in 9.0 s and then 160 m north in 18.0 s. **Calculate** the runner's:

a displacement

b average speed

c average velocity.

★ 9 **Calculate** and complete Table 1 to practise applying the acceleration formula.

TABLE 1

	v (m s^{-1})	u (m s^{-1})	t (s)	a (m s^{-2})
a	100	40	3.5	?
b	60	130	0.85	?
c	250	?	1.5	4.0

★ **10** A car with an initial velocity of 3.0 m s^{-1} has a velocity of 34 m s^{-1} after 3.0 s. **Calculate**:

- **a** its acceleration
- **b** its average velocity
- **c** how far it moved in its third second of motion
- **d** its speed after travelling 20 m.

★ **11** **Calculate** the missing data in the cells in Table 2.

TABLE 2

	s (m)	*u* (m s^{-1})	*v* (m s^{-1})	*a* (m s^{-2})	*t* (s)
a		0		3	1.5
b	200	0			1.4
c		20	65	2.6	

★★ **12** A cyclist is travelling at a constant 10 m s^{-1} when he begins to ride without pedalling up a hill. Assuming the cyclist decelerates uniformly at 1.8 m s^{-2}, **calculate**:

- **a** how far the cyclist will travel before coming to rest.
- **b** how long this will take.

★★ **13** In the 1993 British Motorcycle Grand Prix, Kevin Schwantz was eliminated after a crash. *Australian Motorcycle News* described the crash: 'Schwantz was the first to crash after asking too much of a cold rear tyre. He hit the grass at 290 km h^{-1} and slid to a halt in a set of sand traps 50 m down the track.' **Calculate** Schwantz' deceleration in this accident.

★★ **14** Suppose a rocket ship in deep space moves with a constant acceleration of 9.8 m s^{-2}, which gives the illusion of normal gravity during the flight.

- **a** If it starts from rest, **calculate** the time it will take to reach a speed one-tenth that of the speed of light (speed of light is 3×10^8 m s^{-1}).
- **b** **Calculate** how far it will travel in doing so.

★★★ **15** Imagine two rocks are dropped off a cliff 1 s apart. As they fall to the ground below, does the distance between them get bigger? **Explain**.

★★★ **16** A stone is dropped off a bridge 50 m above the water. Exactly 1 s later another stone is thrown down and both stones strike the water together.

- **a** **Calculate** the initial speed of the second stone.
- **b** **Sketch** a velocity–time graph of both stones on the same graph.

Apply, analyse and interpret

★ **17** **Clarify** whether the following statements about motion, are true or false:

- **a** When a ball is thrown vertically, it has an acceleration of −9.8 m s^{-2} on its way up and down, but zero acceleration at the top.
- **b** When an object travels in a straight line, the displacement equals distance travelled.
- **c** An object slowing down has negative velocity.
- **d** Time is a vector quantity because it has a forward and backward direction.

★ **18** The graph in Figure 3 shows the displacement of a radio-controlled car being driven in a straight line:

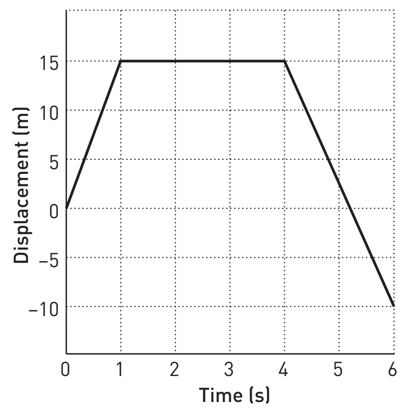

FIGURE 3 Displacement of a radio-controlled car being driven in a straight line

- **a** **Determine** at what stage its velocity was the greatest.
- **b** **Determine** when it was stationary.
- **c** **Determine** when its velocity was constant but not zero.
- **d** **Determine** what its velocity was at 5 s.

★ **19** The graph in Figure 4 shows the motion of a girl on rollerblades as a function of time.

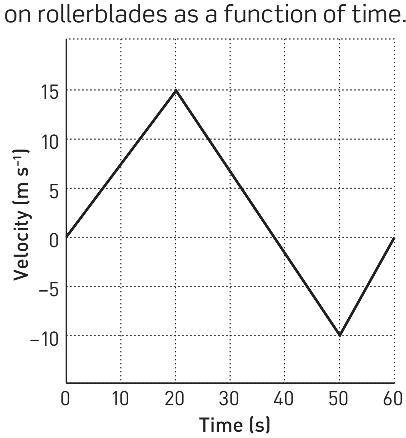

FIGURE 4 Motion graph of a girl on rollerblades

a **Calculate** her displacement after 50 seconds.

b **Calculate** the distance she travelled in the minute.

c **Determine** at what stage her acceleration was the greatest.

d **Determine** when she was stationary.

e **Determine** when her velocity was constant but not zero.

★★ **20** **Consider** a case where air resistance is taken into account. A tennis ball was dropped from a 120 m high cliff and accelerated uniformly to a maximum speed of 20 m s^{-1} after 5 s. From then on to the ground it travelled at this speed. **Calculate**:

a the ball's acceleration over the first 5 s

b how far it travelled before it reached maximum speed

c its total time of flight

d its impact velocity

e its average velocity for the entire flight.

★★ **21** The single cable supporting a construction elevator breaks when the elevator passes the sixth floor (25 m) on its way up while at a speed of 3.0 m s^{-1}.

a **Calculate** the elevator's velocity on impact.

b **Determine** how much time will elapse before the elevator strikes the ground.

★★★ **22** A basketball player, standing near the basket to grab a rebound, jumps 76.0 cm vertically.

a On his way up, **calculate** how much time he spends:

i in the bottom 15 cm of his jump.

ii in the top 15 cm of his jump.

b **Determine** whether this helps explain why such players seem to hang in the air at the tops of their jumps.

★★★ **23** A juggler tosses balls vertically into the air. **Determine** how much higher they must be tossed if they are to spend twice as much time in the air.

★★★ **24** A person standing on the edge of a cliff throws a ball straight up with speed *u*, allowing it to crash onto the rocks below. The person later throws a ball with the same speed *u* straight down. **Determine** which ball has the higher speed when it hits the rocks. Ignore air resistance.

Investigate, evaluate and communicate

★ **25** Perform simple calculations to **solve** for the missing values in Table 3.

TABLE 3

	Displacement	Time	Velocity
a	300 m	6 s	
b	150 km	4 h 30 min	
c		30 s	340 m s^{-1}

★★★ **26** The Sukhoi Su-29 is a Russian-built two-seat aerobatic competition aircraft becoming popular in Australian competitions. If this aircraft was flying at its cruising speed of 160 knots (298 km h^{-1}) and an altitude of 1000 m, and suddenly encountered terrain sloping upward at 4.3° (an amount difficult to detect), **determine** how much time the pilot would have to make a correction if they were is to avoid flying into the ground.

★★★ **27** An article in a newspaper quoted a safety expert as saying: 'An unrestrained child in a 50 km h^{-1} car crash suffers the same effects as being dropped onto concrete from a building's second floor. It is claimed by some parents that merely placing children in the back seat would protect them in a crash.' **Explore** these comments and confirm or refute them, making whatever approximations are required.

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CHAPTER 11

Forces

For a feat of strength from the natural world, you have to admire Robert Galstyan of Armenia. It seems incredible that a man could start railway wagons moving just by pulling on a rope with his teeth. He did just that in 1992. Galstyan set a world record by pulling two carriages a distance of 7 m with his teeth. How could a 100 kg man accelerate 220 tonnes of railway carriages from rest? If he knew about Newton's laws of motion, he may not have tried.

There have been many misconceptions about forces. Many of these go back 2000 years to Aristotle's idea that a moving object had an internal source of 'impetus', which it was given when first thrown or moved.

OBJECTIVES

→ Define Newton's three laws of motion and give examples of each.
→ Identify forces acting on an object.
→ Construct free-body diagrams representing forces acting on an object.
→ Determine the resultant force acting on an object in one dimension.
→ Solve problems using each of Newton's three laws of motions.

Source: *Physics 2019 v1.2 General Senior Syllabus Queensland Curriculum & Assessment Authority*

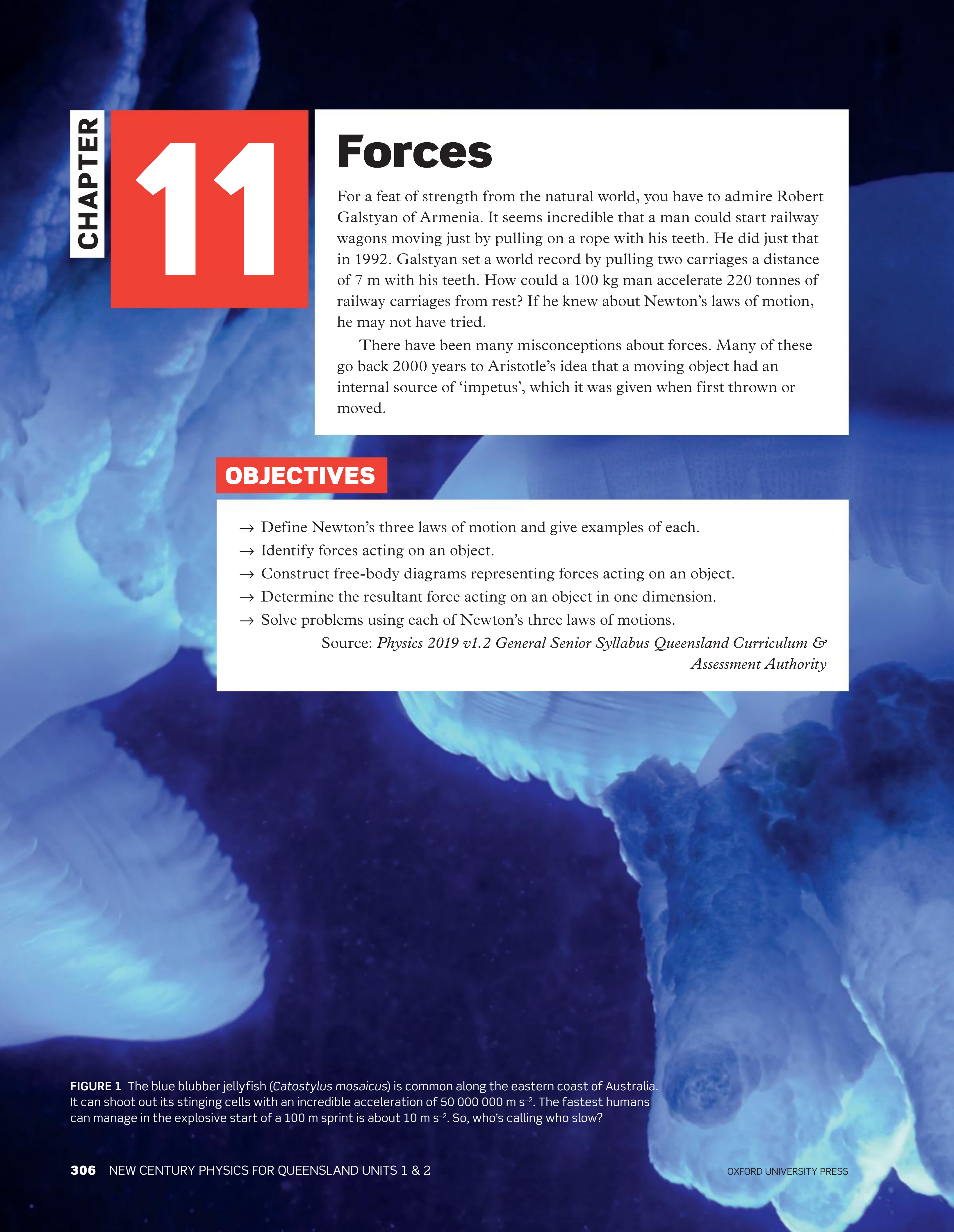

FIGURE 1 The blue blubber jellyfish (*Catostylus mosaicus*) is common along the eastern coast of Australia. It can shoot out its stinging cells with an incredible acceleration of 50 000 000 m s^{-2}. The fastest humans can manage in the explosive start of a 100 m sprint is about 10 m s^{-2}. So, who's calling who slow?

MAKES YOU WONDER

People have often been baffled by questions about forces. In this chapter you will learn about Newton's laws and concepts of motion and how to answer questions such as:

→ After you shoot an arrow, does it keep going until the force runs out?

→ If it takes a force to keep an object moving, why doesn't the Moon crash into Earth?

→ Why do racing cars have 'spoilers' to increase wind resistance when really they want to go faster?

→ Are there any forces acting on you if you're weightless?

→ Cream seems denser than milk, so why does it float on top?

→ Cork doesn't have much weight – but could you lift a ball of cork that is 1 m in diameter?

→ Can rockets take off faster if they have a concrete launch pad to push against?

→ Which weighs more – a tonne of feathers or a tonne of lead?

11.1 Measuring and drawing forces

KEY IDEAS

In this section, you will learn about:

- contact and non-contact forces
- what a force is
- how force is measured
- what a balanced and an unbalanced force is
- calculating a balanced or unbalanced force
- scalar and vector quantity.

Objects travelling in space keep going at constant velocity when there is no external force acting on them. The Voyager spacecraft left our solar system several years ago and is still travelling long after the jets ran out of fuel. On the other hand, a hockey ball rolls to a stop because frictional forces act on it and slow it down.

An ice skater will continue at constant velocity until she tries to turn. The turning is a change in direction and hence a change in velocity. She will slow down unless she pushes off again.

Galileo Galilei (1564–1642) used the same logic to conclude that it is unbalanced forces that cause objects to slow down and stop. We call this force friction – a force that resists motion between two surfaces in contact. Galileo took the word from the Latin *fricare* meaning 'to rub'. Galileo's ideas were very bold for his time because he was not able to verify them experimentally. He ended up in hot water with authorities of the Church when he asserted that other planets were much the same as Earth and revolved around the Sun, whereas the Church taught that the Sun revolved around Earth.

force
a push or pull between objects that may cause an object or both objects to change speed and/or the direction of their motion or change their shape (symbol: *F*; SI unit: newton; unit symbol: N)

What is a force?

Force is a push or pull between objects that may cause one or both objects to change speed and/or the direction of their motion (such as accelerate) or change their shape.

Scientists have identified four fundamental forces: gravitational, electromagnetic (involving both electrostatic and magnetic forces), weak nuclear forces and strong

FIGURE 1 The Voyager spacecraft just keeps on moving even though it ran out of fuel long ago.

nuclear forces. All interactions between matter can be explained as the action of one, or a combination, of these four fundamental forces. There are other non-fundamental forces you will come across such as the normal force, tension, friction, elastic force, centripetal force and even a fictitious one – centrifugal force.

Types of forces

Forces can be simply divided into two types: contact and non-contact.

- **Contact forces** are those where the object and the action producing the force touch each other. Examples are everyday pushes and pulls (lifting a bag, walking, throwing a ball, pushing a car home).
- **Non-contact forces** are action-at-a-distance forces such as gravity, magnetism and electrostatic forces. They are sometime called 'field forces' because they act by way of a field, such as magnetic field or gravitational field. For example, Maglev trains float on opposing magnetic fields; gravity pulls a rock towards Earth through its gravitational field; rub a pen on your jumper and you can pick up little bits of paper with an electrostatic force in an electric field.

contact force
a force where the object and the action producing the force touch each other

non-contact force
an action-at-a-distance force that acts on an object without coming physically in contact with it

Students often ask, 'What does "contact" mean?'. When two objects are in contact, it is simply one electron cloud pushing against another electron cloud, and the atoms don't touch. It's enough that if any part of an atom touches another part, then 'contact' has been made.

Agents and receivers

It is easy to think of forces being made up of an **agent** (that produces the force) and a **receiver** (that responds to the force). But sometimes it is not clear which one came first so the distinction is irrelevant. The important thing to remember is that a force only acts when there is something for it to act on.

agent
the body that produces the force

receiver
the body that responds to the force

Measuring force

The unit of force is named after one of the world's greatest physicists, Isaac Newton. The newton (N) is commonly measured in the laboratory with a spring balance (Figure 2). This has a spring that extends when masses are hung on it or when other forces are applied. The scale is calibrated in grams for mass or newtons for force. Because the direction of the force is important, force is a vector quantity.

The size of one newton is not familiar to most people. The 'feel' of a newton helps you in your problem solving. To use a spring balance, it must first be adjusted to read zero when held vertically. When you pull gently on the spring balance, you can pull to feel forces of 1 N, 2 N, 3 N, etc. If you hang masses on the hook of the spring balance, it will show what force is needed to hold them up.

Different distributions of force and weight can be applied in different situations. Some car manufacturers believe that a 50:50 weight distribution between front and rear tyres is ideal, but when racing and time around the track is key, a weight ratio of 40:60 is more common. This is because it gives you better acceleration, corner entry and corner exit.

FIGURE 2 A school spring balance with a scale in grams. Some balances also have a scale in newtons.

Drawing forces – scalar and vector quantities

Forces are vector quantities and can be represented in two ways:

- by arrows (→) – the length of the arrow represents the magnitude of the vector quantity, and the direction of the arrow shows the direction of the force. Sometimes these arrows are called 'directed line segments'.
- by making the symbol for the quantity bold, such as $\boldsymbol{F}$ – when the symbol is not bold (F), we are just interested in the magnitude of the force and not considering its vector nature.
- by using an arrow above the symbol, such as $\vec{F}_N$.

Figure 3 shows four forces acting on an object. Figure 3(a) shows a *Swatkat* turbo-jet fighter in flight. When the thrust and drag are equal and opposite, the jet flies at constant speed. When lift and weight are equal and opposite, the jet maintains its altitude. Figure 3(b) is a simplified free-body diagram of the jet fighter with arrows representing the force vectors. Their length is proportional to their magnitude. The thrust-to-weight ratio is 0.55, which is a bit underpowered for a jet.

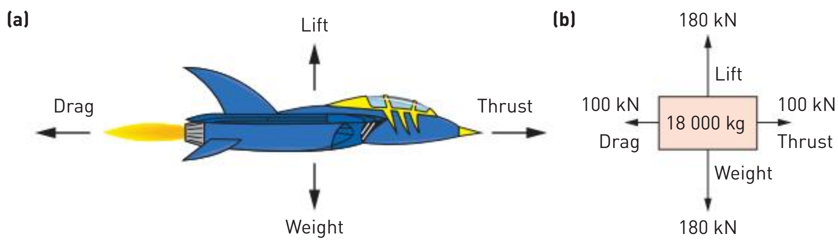

FIGURE 3 (a) *Swatkat* turbo-jet fighter in flight; (b) Simplified free-body diagram of the jet fighter with arrows representing the force vectors

Balanced and unbalanced forces

balanced forces
two forces acting in opposite directions on an object, and equal in size; they do not cause a change in the motion of an object

unbalanced forces
forces that cause a change in the motion of an object; also called non-balanced forces

To study the effect of forces acting on an object, we need to distinguish between **balanced forces** and **unbalanced forces**. When spring balances are hooked onto either end of a cart at rest and given equal pulls in opposite directions (Figure 4), the carts remain at rest because the forces are balanced – they are equal and opposite. We say that balanced forces do not cause a change in the motion of an object. By 'change' we mean it remains at rest or at constant velocity. It does not accelerate.

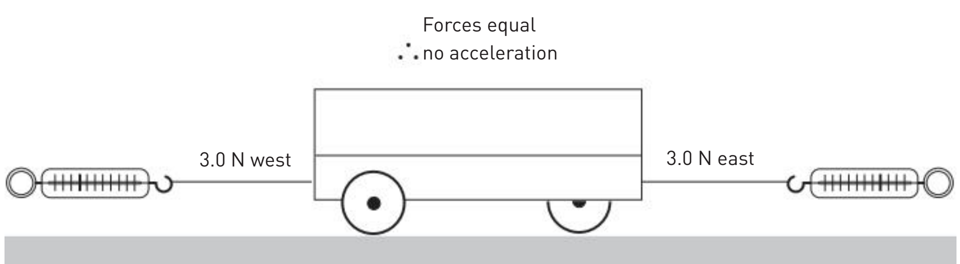

FIGURE 4 The forces on the cart are balanced – they are equal and opposite in direction.

If the pull on the balance to the right was increased to 5 N (as shown in Figure 5), then the forces would become unbalanced and the cart would start to move in the direction of the larger force (to the right). We say that unbalanced forces cause a change in the motion of the object – the object accelerates (speeds up, slows down or changes direction).

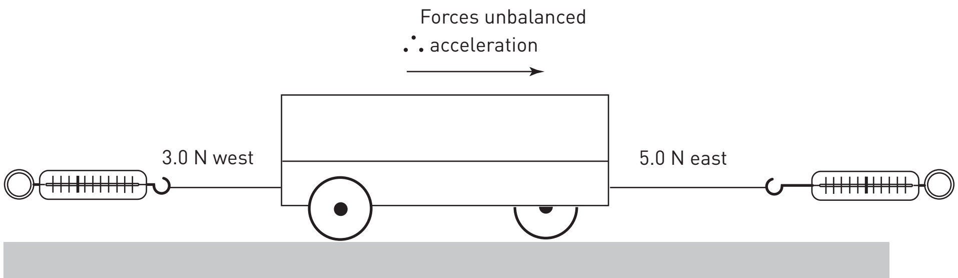

FIGURE 5 The force on the cart is unbalanced – it is greater to the right than to the left.

Study tip

Note that the symbol for force, $\mathbf{F}$, is shown in bold as we are considering force as a vector (magnitude and direction). If you are just talking about the magnitude of the force, then the symbol is non-bold F.

WORKED EXAMPLE 11.1

Calculate the resultant force acting on the cart in Figure 5. It seems obvious, but it is important to get the setting-out of the solution correct.

SOLUTION

Finding the resultant force is a vector addition.

$\mathbf{F}_R = \mathbf{F}_1 + \mathbf{F}_2$ (note that the symbols are bold to indicate a vector quantity)

= 5.0 N east + 3.0 N west (magnitude and direction stated)

= 5.0 N east + (−3.0 N east)

= 2.0 N east

CHECK YOUR LEARNING 11.1

Describe and explain

1 **Describe** a contact force.

2 **Explain** what a force is.

3 **Explain** two differences between a contact force and a non-contact force.

4 **Explain** what the length of a vector arrow represents.

5 **Describe** how the *Swatkat* (Figure 3) jet maintains altitude.

6 Using an example, **explain** a balanced force.

Apply, analyse and interpret

7 The average mass of Sumo wrestlers in 1994 was 136 kg. In 2018 their average mass had risen to 168 kg. If this trend continues, when will they no longer be able to stand up? (The maximum mass that two legs can carry is 180 kg.)

8 **Consider** why you lean forward when you get up out of a chair.

9 **Interpret** the scale reading for the spring balances in Figure 6.

FIGURE 6 Spring balances

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Force

» Weblink
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11.2 Newton's first law

KEY IDEAS

In this section, you will learn about:

+ the development and application of Newton's first law of motion.

We have no trouble today saying what causes motion. You will have learnt that it is a push or a pull. However, it is not that simple. The greatest scientific minds in history have struggled with working out the causes of motion. Aristotle (384–322 BCE), Ptolemy (100–170 CE), Copernicus (1473–1543), Galileo (1564–1642) and Newton (1642–1727) developed many complex models and theories describing motion and force throughout the ages.

The Greek idea of motion was developed by Aristotle more than 2000 years ago. He proposed that objects have a natural state, and that if left alone would try to attain this state. By the time of Galileo, it was evident that this idea had serious problems.

Galileo showed that Aristotle was wrong about forces being necessary to keep objects in motion. Although a force is needed to start an object moving, Galileo showed that, once it is moving, no force is needed to keep it moving except for the force needed to overcome **friction**.

friction
the force that resists motion between two surfaces in contact

When friction is absent, a moving object needs no force to keep it moving – it will remain in motion all by itself. Galileo used wooden balls on a ramp to show this – the balls rolled rather than slid, which meant friction was very low. Figure 1 summarises Galileo's investigation. In the first test, the arms of the incline plane are at the same height and a ball, once released, travels along the ramp and rises to the same height. When the second arm is longer, the ball travels further but still continues until it finds the same height. In the third test, Galileo realised that if the second arm didn't rise then the ball would travel at constant speed forever.

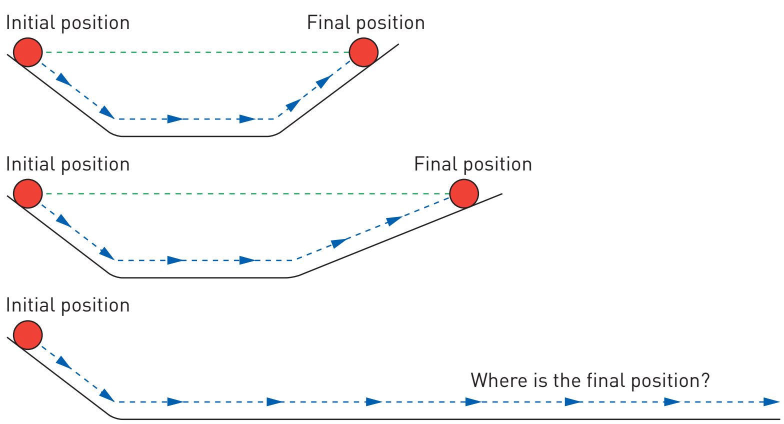

FIGURE 1 Galileo's investigation showed that once an object is moving, it needs no force to keep it moving

Newton put Galileo's ideas into the form of a universal physical law – a law that is obeyed throughout the universe. This eventually became his first law. Over time, Newton developed many complex models and theories that were based on a range of evidence, some of which was provided by predecessors such as Ptolemy, Aristotle, Copernicus and Galileo. As Newton said in 1676, 'If I have seen further, it is by standing on the shoulders of giants.'

In 1688, Newton proposed his first law of motion (translated from the Latin):

Newton's first law of motion: an object maintains its state of rest or constant velocity motion unless it is acted on by an external unbalanced force.

Newton's first law
an object maintains its state of rest or constant velocity motion unless it is acted on by an external unbalanced force

The following examples show Newton's first law applied to real life.

At rest and stays at rest

Some magicians can jerk a tablecloth out from under a dinner setting of glasses and cutlery, leaving them at rest on the table.

In motion and stays in motion

In a head-on car crash, the occupants tend to continue in their state of motion and move forward towards the dashboard. It is usually the seat belts that restrain them.

Continuing in the same direction

As a car goes around a corner, your body continues in a straight line until the car door presses against you as the car moves sideways. People often say they get flung against the car door, but it is actually the door that gets flung against them.

Balanced forces, constant velocity

Consider a diagram of the forces acting on a car travelling along a road at constant velocity (Figure 2). When this car travels at constant velocity, all the forces acting on it are balanced. The downward force of the car on the road is balanced by the upward force of the road on the car. The force produced by the engine is balanced by the friction of the tyres on the road and the air resistance, as well as friction within the moving parts of the car. As long as these forces remain balanced, the car will not accelerate.

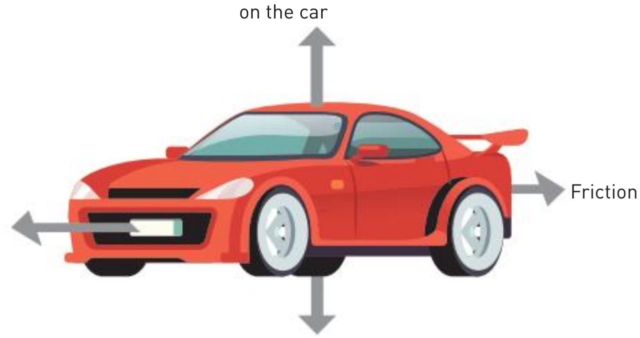

FIGURE 2 If the forces are equal and opposite (balanced), the car will not accelerate.

CHECK YOUR LEARNING 11.2

Describe and explain

1 **Explain** Aristotle's original proposal about objects having a natural state.

2 **Describe** Galileo's test for friction and movement.

3 Using your own words, **explain** Newton's first law.

4 **Describe** examples of Newton's first law when an object is:

- a at rest and stays at rest
- b in motion and stays in motion
- c continuing in the same direction
- d experiencing balanced force and constant motion.

Investigate, evaluate and communicate

5 A thread supports a mass hanging from the ceiling. Another identical thread is tied to the bottom of the mass (Figure 3).

Predict which thread is likely to break if the bottom thread is pulled:

- a slowly
- b quickly.

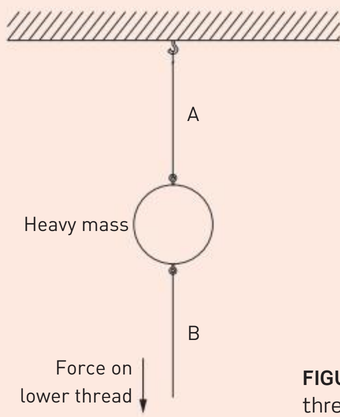

FIGURE 3 A mass with two threads attached

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What is mass?

» Weblink
Newton's first law

» Weblink
Isaac Newton

11.3 Newton's second law

KEY IDEAS

In this section, you will learn about:

+ Newton's second law
+ unbalanced forces and acceleration.

Newton's second law
the acceleration of an object is in the direction of the net external force acting on it and proportional to the size of the force and inversely proportional to the mass

mass
a characteristic of a body's resistance to change in motion; also called inertia

Newton's first law deals with cases where the forces are balanced, so no acceleration occurs. **Newton's second law** deals with unbalanced forces and hence acceleration will occur.

Everyday experience tells us that a given force will produce different accelerations in different objects. Kick a football and it moves off quickly, but kick a car and it hardly moves. The difference is their **mass** – the car has a greater mass than the ball. Mass is measured in units of kilograms, although grams and tonnes are widely used.

Newton's second law: the direction of the acceleration of an object is in the direction of the net external force acting on it and proportional to the size of the force.

$$\boldsymbol{a}_{\text{net}} = \frac{\boldsymbol{F}_{\text{net}}}{m}$$

where $\boldsymbol{a}_{\text{net}}$ is the acceleration of the object, $\boldsymbol{F}$ net is the net force acting on the object, and m is the mass of the object.

Here are some real-life examples of Newton's second law:

- Dropping a rock over a cliff – there is no upward force to balance the force of gravity (assuming we neglect air resistance).
- A bullet travelling out of a rifle barrel – the force due to the pressure of hot expanding gases is greater than the friction from the walls of the barrel.
- Driving away from traffic lights – the force produced by the engine is greater than the friction of the tyres and air resistance, so a car will accelerate.
  - The heavier the car, the more force is needed to accelerate away from the traffic lights.
  - The faster you want to accelerate, the greater the force needed.
  - The acceleration occurs in the direction of the unbalanced force.

Newton's second law accounts for these facts. Newton derived his relationship from theory, not from experiment. It has since been verified experimentally (perhaps a billion times!).

The unit of force is the newton (N), and a newton is defined as the force needed to give a 1 kg object an acceleration of 1 m s^{-2}.

Study tip

When working out problems involving Newton's second law, it is common to write the equation in its non-vector form and leave out the subscripts 'net' as this is understood. The formula then becomes $a = \frac{F}{m}$ or $F = ma$.

WORKED EXAMPLE 11.3

An unbalanced force of 48 N west is applied to a 6.0 kg cart. Calculate the cart's acceleration.

SOLUTION

$$\boldsymbol{a}_{\text{net}} = \frac{\boldsymbol{F}_{\text{net}}}{m} = \frac{48 \text{ N west}}{6.0 \text{ kg}} = 8.0 \text{ m s}^{-2} \text{ west}$$

Note that force is considered to be a vector quantity here, so a bold ***F*** is used; likewise for ***a***.

Introducing tension

Tension is the pulling force transmitted along a rope, string, cable or chain on an object. We use the symbol $\boldsymbol{F}_{\mathrm{T}}$ to show that it is a force, with the subscript T to signify that it is 'tension' – a pulling force and not compression or any other sort of force.

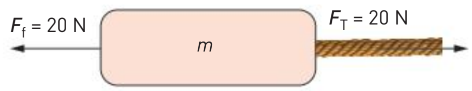

FIGURE 1 Tension is a pulling force only

tension
the pulling force transmitted along a rope, string, cable or chain on an object

For example, when a force of 20 N is applied to the block through the rope in Figure 1, we say the tension in the rope is 20 N.

Introducing applied force

An **applied force** (F_A) is the force applied to an object by a person or another object. It can be a push or a pull – so if you push a desk across the room, then your hands are providing an applied force on the desk. If you pull a cart by a rope, then you are providing an applied force through the tension in the rope on the cart.

applied force
a force applied to an object by a person or another object; can be a push or a pull

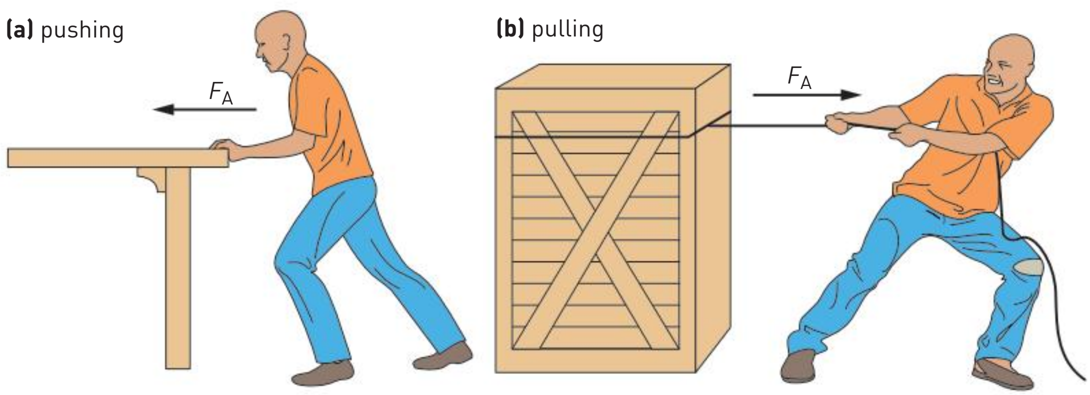

FIGURE 2 Pushing and pulling forces are applied forces on the object.

Examples of Newton's second law

CHALLENGE 11.3A

Braking

For most cars, the rear tyres support more weight than the front tyres. For example, a Toyota Corolla has 43% of its weight supported by the front tyres and 57% by the rear. When a Corolla brakes, the weight on the front increases to about 69% and reduces to 31% on the rear. Why is this, and why do cars dip when the brakes are applied?

FIGURE 3 A loop-the-loop by a jet-fighter pilot can cause a loss of consciousness.

Loss of consciousness

Rapid acceleration or deceleration can severely affect the human body. Too high a deceleration can cause loss of consciousness – for example, in a sharp loop-the-loop by a jet-fighter pilot and crew. In extreme cases, it can result in death. Smashing into a power pole can kill a car driver – this is why cars have crumple zones that are designed to slow the rate of deceleration (and hence the size of the force) in an accident.

CHALLENGE 11.3B

Spring balance mass

Figure 4(a) shows a 1 kg mass hanging on a spring balance that indicates a weight of 10 N. Figure 4(b) shows the same 1 kg mass, but this time suspended over a pulley by a string tied to the table. Is the diagram in part (b) correct? Explain.

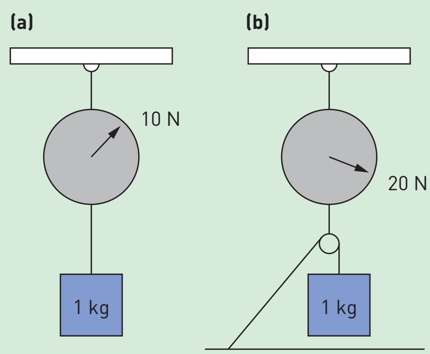

FIGURE 4 Is the diagram in part (b) correct?

CHALLENGE 11.4C

Force applied to a cart

In Figure 5, for m_1 and m_2 to remain in the same positions relative to the cart, what force *F* has to be applied? Assume there is no friction.

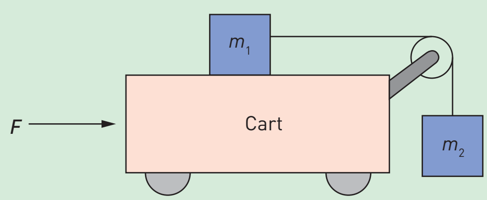

FIGURE 5 What force has to be applied for the masses to remain in the same positions?

CHECK YOUR LEARNING 11.3

Describe and explain

1 Using an example, **describe** Newton's second law.

2 **Explain** the formula $a_{net} = \frac{F_{NET}}{m}$ in relation to Newton's second law.

3 **Calculate** the missing quantities in Table 1.

TABLE 1

	F	m	u	v	a	t
a		1000 kg	rest	25 m s^{-1}		8.5 s
b	25 N	15 kg	rest			2.0 s
c	1000 N		10 m s^{-1}	40 m s^{-1}	10 m s^{-1}	
d		200 g	0.85 m s^{-1}	0.60 m s^{-1}		1.5 min
e	150 N			rest	−2.2 m s^{-2}	4s

4 A car of mass 2000 kg decelerates from 30 m s^{-1} to rest in a distance of 100 m. **Calculate** the unbalanced force required to stop the car.

Apply, analyse and interpret

5 Racing driver David Purley survived a deceleration from 173 km h^{-1} to zero in a distance of 66 cm in a crash at Silverstone, United Kingdom, in 1977. He suffered 29 fractures, three dislocations and six heart stoppages, and he made it into the *Guinness Book of Records*. His body mass at the time was 55 kg. **Determine** the net horizontal force acting on him in the crash.

6 In an experiment to find out how the motion of a trolley was related to the force acting on it, a 1.5 kg trolley was accelerated by various forces. The results are summarised in Table 2.

TABLE 2

Force (N)	0.00	0.10	0.20	0.30	0.40	0.80
Acceleration (m s^{-2})	0.00	0.07	0.13	0.20	0.27	0.53

Classify the relationship that is suggested by the data.

7 In astronaut Neil Armstrong's biography, it says that on Phobos (one of the two potato-shaped moons of Mars) he would weigh only 3 ounces. If *g* on Phobos is one-thousandth that of its value on Earth, **determine** his mass in kg.

Investigate, evaluate and communicate

8 You have been provided with a ball, a stopwatch and a tape measure. How many different ways can you think of to measure the distance from a top-floor veranda to the ground below? **Identify** error sources and comment on the most accurate method.

9 **Comment** on the following claims:

a It requires a greater force to accelerate a 2000 kg car from rest to 15 m s^{-1} than from 15 m s^{-1} to 30 m s^{-1} in the same time.

b Twice the force is needed to accelerate a 1.5 tonne car from rest to 60 km h^{-1} over 100 m than is required over 200 m.

c An object always accelerates in the direction of the net force.

d A lower net force is needed to accelerate an object from rest to 10 m s^{-1} than is required to accelerate it from rest to 20 m s^{-1}, irrespective of the time taken.

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» Student book questions
Check your learning 11.3

» Challenge
11.3A Braking

» Challenge
11.3B Spring balance mass

» Video
Newton's 2nd law set-up

11.4 Newton's third law of motion

KEY IDEAS

In this section, you will learn about:

+ Newton's third law of motion.

In 1687, Isaac Newton argued that if he pushed on a stone there would be an equal and opposite force pushing back.

Newton wrote this as his third law and in Latin used the words *actiones* (actions) and *reactionem* (reaction) in his statement. The law is often stated as 'for every action there is an equal and opposite reaction', but this implies that the reaction follows the action, whereas the action and reaction are actually occurring simultaneously (at the same time).

Newton's third law
forces always occur in equal and opposite pairs

Newton's third law has been greatly simplified to the modern version that avoids the idea of an action and then a reaction:

Newton's third law: forces always occur in equal and opposite pairs.

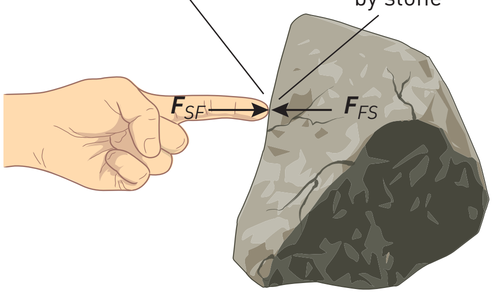


FIGURE 1 Newton used this an example of his third law of motion.

In other words, 'if body A is exerting a force on body B, then body B is exerting an equal and opposite force on body A'. This second way of expressing the law is more involved, but is more precise. Note that the two forces are acting on different objects (A acts on B, B acts on A). Mathematically, and using vector notation, it could be put as:

$$\boldsymbol{F}_{AB} = -\boldsymbol{F}_{BA}$$

with the negative sign indicating they are in opposite directions. If we were just looking at the magnitudes of the forces we would write: $F_{AB} = F_{BA}$.

For example, if you exert a force on a nail by hitting it with a hammer, the nail exerts an equal and opposite force on the hammer. If you lean against a wall, the wall pushes back on you.

Summary

- Each force acts on a different object: A acts on B, and B acts on A.
- Both forces are the same type of force: field and field, or contact and contact.

Examples

Third law force pairs are given in Table 1. The simplest way to work out the pairs is to reverse the order of the two objects.

TABLE 1 Third law force pairs

Force A on B	Force B on A
Exhaust gases are pushed out of the rocket	The rocket is pushed forward by the gas
A sprinter pushes on the starting blocks	The blocks push on the sprinter
A tyre pushes on the road	The road pushes on the tyre
A bat hits a softball	The softball pushes against the bat
An orbiting satellite is attracted to Earth by gravity	Earth is attracted to the satellite by gravity
A vase of flowers is attracted to Earth by gravity	The Earth is attracted to the vase of flowers by gravity

This last example in Table 1 with the vase is the trickiest type to work out as it involves gravity.

CHALLENGE 11.4

Isaac Newton's life

Isaac Newton's early childhood was said to be marked by rejection and hatred. From 1678 to 1696 he conducted experiments by heating up heavy metals such as lead and mercury, breathing in the vapour (sweet, saltish, vitriolic) in the process. It was no surprise that he developed mental illness by 1693. Samples of his hair were tested for mercury and found to have had 200 parts per million (where 5 ppm is normal and 40 ppm dangerous).

Newton has been ranked as the second most influential person in the world (influential – rather than not important). Develop an argument for who might be first and third.

Introducing gravitational force

Gravity is a force that acts through a gravitational field between objects with mass. It is a **field** or non-contact force (as distinct from a **contact** force where the objects physically touch, such as a tyre on the road, or a finger pushing a rock). The **gravitational force** acts over the vast distances of space to the very edge of the known universe.

gravitational force
a force that acts through a gravitational field between objects with mass

Figure 2 shows a man standing on the ground. While he is standing on the ground he experiences the gravitational force pulling him down. Earth also experiences a gravitational force due to the man's body that pulls it upwards. These two forces make up a third law force pair. But the man is prevented from moving too far because the surface (the ground) stops him. His feet press down and the ground presses up to stop him moving downwards.

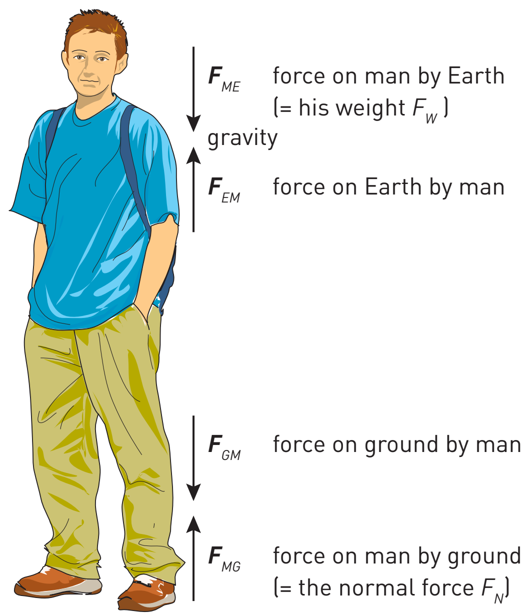


FIGURE 2 The third law force pairs acting on a man standing on the ground. The 'field' forces are one pair and the 'contact' forces are the other pair.

In Figure 2 there are two sets of third law force pairs:

- The top force pair is due to gravity – they are called 'field forces' as they are due to the gravitational field. The force shown as $\boldsymbol{F}_{ME}$ is called the man's 'weight' or $\boldsymbol{F}_W$. The SI convention is to use F for force and different subscripts for specific types of force.
- The bottom force pair is associated with the ground pressing up and the man pressing down – they are called 'contact forces' because they make physical contact with the surfaces. The force $\boldsymbol{F}_{MG}$ is called the 'normal force' or $\boldsymbol{F}_N$. It is a contact force that acts at right angles to the surface.

As the man is not accelerating we can say the net force is zero. So, in this case, the normal force is equal in magnitude to the weight: $F_N = F_W$ (or if being treated as vector quantities, $\boldsymbol{F}_N = -\boldsymbol{F}_W$).

These third law force pairs can also be seen with a box sitting on top of a table as shown in Figure 3.

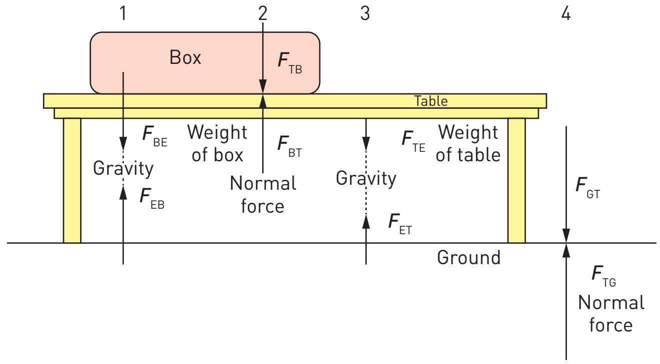
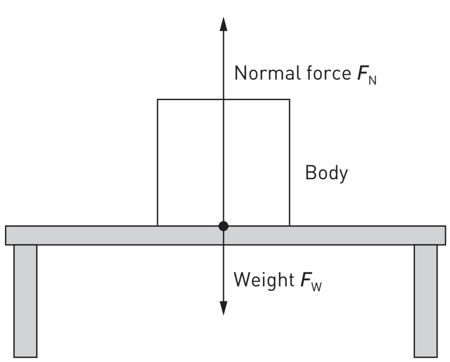


FIGURE 3 Third law forces for a box resting on a table, wh ich is resting on the ground.

TABLE 2 Downward and upward forces a third law force pair

	First force of a third law force pair	Second force of a third law force pair
	Downward:	**Upward:**
1	$\boldsymbol{F}_{BE}$ Field force on **the box by Earth**, called the weight of the box.	$\boldsymbol{F}_{EB}$ Field force on **Earth by the box**. $(\boldsymbol{F}_{EB} = -\boldsymbol{F}_{BE})$
2	$\boldsymbol{F}_{TB}$ Contact force on **the table by the box**.	$\boldsymbol{F}_{BT}$ Contact force on **the box by the table**, called the normal force of the table pushing up on the box. $(\boldsymbol{F}_{BT} = -\boldsymbol{F}_{TB})$
3	$\boldsymbol{F}_{TE}$ Field force on **the table by Earth**, called the weight of the table.	$\boldsymbol{F}_{ET}$ Field force on **Earth by the table**. $(\boldsymbol{F}_{ET} = -\boldsymbol{F}_{TE})$
4	$\boldsymbol{F}_{GT}$ Contact force on **the ground by the table**.	$\boldsymbol{F}_{TG}$ Contact force on **the table by the ground**, called the normal force of the ground pushing up on the table. $(\boldsymbol{F}_{TG} = -\boldsymbol{F}_{GT})$



Two notable forces are $\boldsymbol{F}_{BE}$, the weight of the box acting down, and $\boldsymbol{F}_{BT}$, the normal force that the table pushes up with perpendicular to the surface. ‘Normal’ means at right angles (Figure 4). The normal force is the force acting along an imaginary line drawn perpendicular to the surface.

FIGURE 4 Two forces of interest. If there is no acceleration, we can say $\boldsymbol{F}_N = -\boldsymbol{F}_W$ (i.e. magnitudes $F_N = F_W$) even if they are not a third law force pair. If the mass of the box was 1 kg, then the weight would be approximately 9.8 N down and the normal force would be 9.8 N upward. The vector sum ($\boldsymbol{F}_{net}$) is zero.

Does F_N always equal F_W?

Imagine you now push downwards on the top of the box with your finger (Figure 5). The weight of the box does not change, but the normal force will now increase to be equal to the weight plus the extra force applied.

We can now say magnitudes $F_N = F_W + F_{push}$. As the box does not accelerate, $F_{net} = F_N - F_W - F_{push} = 0$.

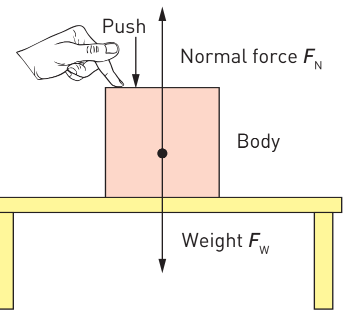


FIGURE 5 The normal force can be greater than the weight.

CHECK YOUR LEARNING 11.4

Describe and explain

1 **Explain** Newton's third law.

2 **Explain** why it is important to think of the forces in Newton's third law occurring simultaneously rather than as an action and then a reaction.

3 Using an example, **describe** how forces act simultaneously.

4 **Identify** the paired forces in the following:

   a A tennis ball is hit by a racquet.

   b A horse walks along a road.

   c A horse drags a log along a dirt track.

   d A click beetle jumps into the air.

   e A man falls out of a tree.

5 The main gun on the British warship HMS *Invincible* had a bore (internal diameter) of 16 inches (40 cm) – that's huge! Its shells could penetrate 24 inches (60 cm) of steel armour on enemy ships. The recoil of the gun was so great that it would buckle the wooden deck and peel off the paint. **Identify** the paired forces.

Apply, analyse and interpret

6 A vase of mass 2.5 kg rests on a table.

   a **Identify** the normal force exerted by the table on the vase.

   b **Consider** what the forces would be if a very large mass of 500 kg was placed on the table.

7 To make your car go forward without using any fuel, just place a magnet in front of the car and the unlike pole on the car will be attracted forward (Figure 6). **Identify** and consider the problem relating to Newton's third law in this suggestion.

FIGURE 6 Would this work?

8 Isaac Newton's mother said that he would fit into a 'quart pot' at birth. If the density of a baby is 1020 kg m^{-3}, **determine** Newton's mass at birth.

Investigate, evaluate and communicate

9 A horse is harnessed to a cart (Figure 7). A student writes, 'The horse tries to pull the cart, so the horse exerts a force on the cart. By Newton's third law, the cart must then exert an equal and opposite force on the horse.'
Evaluate the student's statement.

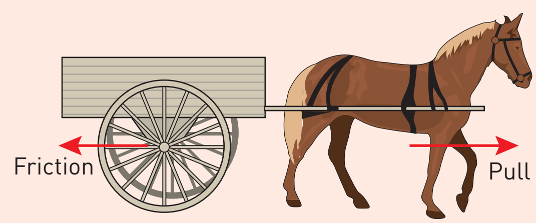


FIGURE 7 A horse harnessed to a cart

10 Some people say that Newton discovered the laws of motion, but others say he invented them. **Assess** who would be correct.

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» Student book questions
Check your learning 11.4

» Challenge
11.4 Isaac Newton's life

» Increase your knowledge
Make your bike faster

» Weblink
Newton's third law

11.5 Force, weight and gravity

KEY IDEAS

In this section, you will learn about:

+ understanding weight and mass
+ how gravity interacts with weight, mass and force.

Force due to gravity

Objects near or on the surface of Earth are attracted towards Earth's centre by a pulling force – gravity. Gravity causes freely falling objects to move downward with an acceleration of 9.8 m s^{-2}. This value is fairly constant over the surface of Earth, but as Earth is not a perfect sphere and the distribution of mass is not even, it does vary from, for example, 9.76 m s^{-2} (Peru) to 9.83 m s^{-2} (Arctic Ocean). This value is not dependent on the mass of the object.

CHALLENGE 11.5

What will fall first?

To see gravity in action, you can use a ball of scrunched up paper and a marble. If you drop these objects from the same height at the same time, they will hit the floor at the same time. If the paper was not scrunched into a ball, it would not hit the ground at the same time as the marble because air resistance would slow the paper's descent.

weight
a measure of the force of gravity acting on an object

If you drop a rock, it will accelerate downward at 9.8 m s^{-2} provided that no other external forces interfere with its motion. This is called free-fall acceleration. The size of the force causing this is derived from $\boldsymbol{a} = \frac{\boldsymbol{F}}{m}$ *or* $\boldsymbol{F} = m\,\boldsymbol{a}$ according to Newton's second law. For a 1 kg rock, the force of gravity equals 1 kg × 9.8 m s^{-2} or 9.8 kg m s^{-2} directed downward. This is 9.8 N and it is the weight of the rock. It has the symbol F_w.

FIGURE 1 Gravity is the force of attraction between two bodies with mass. On Earth, we experience it as pulling objects towards the Earth's centre.

Weight and mass

The term **weight** has been around for a long time, hence the confusion when a common term is given a specific meaning in physics. Weight comes from pre-historic German where *wegan* meant 'to carry'. Its secondary use, meaning 'heaviness' was an Old English adaptation. Weight is different to mass. Mass is a measure of an object's resistance to motion – it doesn't vary no matter where the object might be taken to in the universe.

The formula relating mass to weight is:

$$F_w = mg$$

where g is the local acceleration due to gravity.

On Earth, $g = 9.8$ m s^{-2}, but on other planets and satellites it depends largely on the planet's mass (Table 1).

TABLE 1 Acceleration due to local gravity on some heavenly bodies

Celestial body	Number of Earth masses	Acceleration relative to Earth *g*
Sun	335 000.0	28.0
Jupiter	317.8	2.53
Saturn	95.2	1.07
Neptune	17.2	1.14
Uranus	14.6	0.89
Earth (average)	1.00	1.00
Venus	0.82	0.90
Mars	0.11	0.38
Mercury	0.06	0.38
Io	0.015	0.18
Moon	0.0123	0.17
Pluto	0.0022	0.07

Changes in gravity

Altitude

The force due to gravity decreases with altitude (the distance above Earth's surface). At an altitude of 400 km (the orbiting altitude of the International Space Station), g is down to 8.8 m s^{-2}. This is about 90% of its surface value. You have to be about 3000 km away from Earth before g is down to half.

Bathroom scales

With scales, gravity pulls downwards with a force we've called weight, $\boldsymbol{F}_W = mg$, and the scales push up with a reaction force normal to the surface, $\boldsymbol{F}_N$. This could also be called the 'scale reading'. In this case, as there is no acceleration, the magnitudes of the two forces are equal, so $F_W = F_N$ and the scales read the weight of the body.

For example, if you have a mass of 70 kg then your weight on Earth is 70 × 9.8 or 686 N. That is:

Weight (N) = mass (kg) × 9.8 m s^{-2}

The free-fall acceleration on the Moon (g_{Moon}) is 1.6 m s^{-2}, so your 70 kg mass would give you a weight on the Moon of:

$$F_W = mg_{Moon} = 70 \times 1.6 = 112 \text{ N}$$

If you want to lose weight, fly to the Moon.

FIGURE 2 With bathroom scales gravity and force act together to read the weight of the body.

WORKED EXAMPLE 11.5

An astronaut has a mass of 85.0 kg. Calculate the astronaut's weight on:

a Earth

b the Moon ($g = 1.6\ \text{m s}^{-2}$)

c Jupiter ($g = 24.9\ \text{m s}^{-2}$).

SOLUTION

a $F_w = mg = 85.0 \times 9.8 = 833$ N (830 N to 2 sf).

b $F_w = mg = 85.0 \times 1.6 = 136$ N (140 N to 2 sf).

c $F_w = mg = 85.0 \times 24.9 = 2116.5$ N (2120 N to 3 sf).

CHECK YOUR LEARNING 11.5

Describe and explain

1 **Explain** what weight is.

2 **Explain** how gravity affects weight.

3 **Calculate** the weight and scale reading in newtons of a 70.0 kg person under each of the following conditions:

   a floating in water

   b free-falling off the stage at a concert.

4 A marble dropped from height *h* on Earth takes *t* seconds to reach the ground. **Calculate** the new height in terms of *h* that the ball would need to be dropped from on the Moon to have the same drop time *t*.

Apply, analyse and interpret

5 **Contrast** weight and mass using an example.

6 Using your understanding of weight and mass, **analyse** why it is easier to lift people in a swimming pool but a rubber brick lifted in a pool may still feel heavy.

7 **Determine** how many times heavier by weight a person would be on Saturn than on Earth.

Investigate, evaluate and communicate

8 In hospitals, newborn babies have their 'weight' recorded in grams but this is often converted to pounds and ounces for the parents' benefit.

   a If a woman had a 7 lb 8 oz baby, **calculate** its weight. (1 kg = 2.2 lb; 16 oz = 1 lb)

   b If the baby was born in the 'weightless' conditions of outer space, **propose** how the parents could measure the baby's Earth weight for the benefit of relatives at home.

9 A lawyer emailed a physicist wanting to know what was meant when someone was 'in an accident and suffered high g-forces'. **Discuss** how you would explain it in a few paragraphs.

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» **Student book questions**
Check your learning 11.5

» **Challenge**
11.5 What will fall first?

» **Weblink**
Changes in gravity

» **Weblink**
Gravity in space

11.6 Friction

KEY IDEAS

In this section, you will learn about:

+ the causes and effects of friction.

Consider what life would be like without friction. It would be a nightmare – in fact, impossible!

- You couldn't swallow, walk, hold a pen or do your homework.
- Your clothes would unravel and your shoe laces would come undone.
- Nails and screws would be useless – your house would fall down.
- Mountains would crumble and television cameras couldn't record it.
- Childbirth would be impossible.
- Life would last about one day before everyone died. The farewell party would be a disaster because you couldn't hold on to your cup and you couldn't stand up.

Friction is absolutely necessary, but it is also a hindrance. People have searched for thousands of years for ways of altering friction. But the search to understand friction has only gone on for a few hundred years – only since the birth of physics.

What causes friction?

One of the first scientific studies into friction was in the late 1400s by Leonardo da Vinci, who discovered the various properties of friction. Friction is a force that resists motion between two surfaces in contact. Friction can be either **dynamic**, **static** or **rolling**. In 1699, French scientist Guillaume Amontons formulated these properties of friction into the laws we have today.

dynamic
friction between surfaces in motion relative to each other. Also known as sliding or kinetic friction

static
friction between surfaces stationary relative to each other. It is generally higher than dynamic friction

rolling
friction between two surfaces rolling over each other. It is the smallest of all three

adhesion
the tendency of dissimilar surfaces to cling to one another by electrostatic and other forces

At one time it was thought that the surface roughness of materials was the cause for friction, but it is now understood to only have a small effect on friction for most materials. If the surfaces are very rough, the high points touch each other. These high points interfere with sliding and cause friction because of the abrasion or wear that can take place when you slide one object against the other. This is the san dpaper effect, where particles of the materials are dislodged from their surfaces. In such a case, the friction is caused by surface roughness.

Today, an adhesion model is accepted. When two objects are brought into contact, many atoms or molecules in one object are so close to those in the other object that electromagnetic forces attract the molecules of the two materials together. This force is called **adhesion**. Trying to slide one object across the other requires breaking these adhesive bonds. Adhesion is the essence of friction.

Examining friction

Friction is a retarding force and tends to slow things down. It acts at all speeds and accelerations. The term 'at constant speed' means that the applied force in the direction of motion is equal to the friction resisting motion. If the applied force is greater than friction, the object will accelerate. The applied force can never be less than friction.

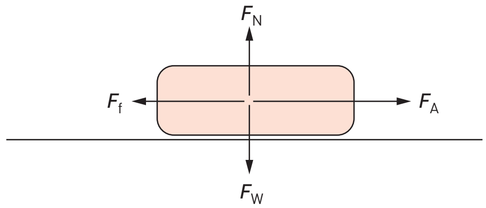

FIGURE 1 A free-body diagram (also called a force diagram) is used to represent applied forces, movements and reactions on a body

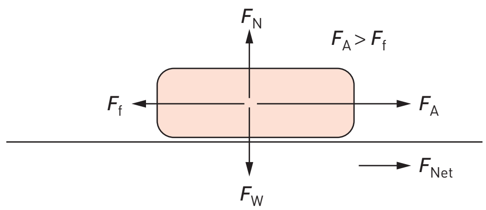

FIGURE 2 Labelling the forces of a free-body diagram

Horizontal applied force

The simplest case for friction between surfaces is when an object moves across a horizontal surface such as a floor or desk. The applied force ($\boldsymbol{F}_A$) and friction ($\boldsymbol{F}_f$) are in a line and oppose each other. As discussed previously, we can construct a **free-body diagram** that shows the basic elements (Figure 1).

The pulling force ($\boldsymbol{F}_A$) is to the right. When moving at constant speed, the magnitude of $\boldsymbol{F}_A$ equals $\boldsymbol{F}_f$. The weight of the block ($\boldsymbol{F}_W$) is opposed by an equal and opposite normal force ($\boldsymbol{F}_N$).

Accelerating objects: pushing or pulling too hard

So far we have looked at objects pushed or pulled at constant speed. If the applied force is greater than that needed to overcome friction, the object will accelerate (Figure 2).

When $\boldsymbol{F}_A$ is greater than $\boldsymbol{F}_f$, the net force ($\boldsymbol{F}_{net}$) will be equal in magnitude to the difference between the two forces, and in the direction of $\boldsymbol{F}_A$ as it is bigger. This will be equal to the product of mass and acceleration ($\boldsymbol{F}_{net} = ma$) according to Newton's second law.

free-body diagram
used to show the relative magnitude and direction of all forces acting upon an object in a given situation

WORKED EXAMPLE 11.6A

A horizontal force of 5.0 N is applied to a 1.0 kg wooden box resting on a laminate benchtop. If the friction is 2.94 N, calculate the motion of the box.

SOLUTION

$\boldsymbol{F}_A = 5.0$ N; $\boldsymbol{F}_W = mg = 1.0 \times 9.8 = 9.8$ N down; $\boldsymbol{F}_N = 9.8$ N up.

$\boldsymbol{F}_{net} = \boldsymbol{F}_A - \boldsymbol{F}_f = 5.0 - 2.94 = 2.06$ N

$$a = \frac{\boldsymbol{F}_{net}}{m} = \frac{2.06}{1.0} = 2.06 \text{ m s}^{-2}$$

in the direction of the applied force.

Note that as force and acceleration are vector quantities, a direction should be stated.

WORKED EXAMPLE 11.6B

A lunchbox with a mass of 800 g is at rest on the floor. It is given a kick and it moves off with a speed of 5.0 m s^{-1}. If the frictional force is 2.352 N, how far will the box slide before it comes to rest?

SOLUTION

$\boldsymbol{F}_W = mg = 0.800 \times 9.8 = 7.84$ N down; $\boldsymbol{F}_N = 7.84$ N up.

$\boldsymbol{F}_f = 2.352$ N. This is the net force ($\boldsymbol{F}_{net}$) in the horizontal direction.

$a = \frac{\boldsymbol{F}_{net}}{m} = \frac{2.352}{0.800} = 2.94$ m s^{-2} (actually -2.94 m s^{-2} if we assume the direction the lunchbox is moving is positive)

$v^2 - u^2 = 2as$

$0^2 - 5.0^2 = 2 \times (-2.94) \times s$

$s = +4.25$ m

The lunchbox moves +4.25 m.

CHECK YOUR LEARNING 11.6

Describe and explain

1 **Explain** the connection between friction and adhesion.

2 **Describe** the forces applied to an object experiencing sliding friction when:
  a pulling at constant speed
  b accelerating.

3 **Identify** if the following are true (T) or false (F). If false, correct the sentence to make it true.
- Forces are needed for motion with constant velocity.
- Objects stop moving when the force is removed.
- Inertia is the force that keeps things in motion.
- The normal force on an object always equals the weight.
- Objects thrown in the air start to fall when they run out of force.

4 A horizontal force of 15 N is applied to a 1.5 kg block on a table for which the frictional force is 7 N. **Calculate** the acceleration of the block.

Apply, analyse and interpret

5 An object of mass 2.0 kg is at rest on a lab bench. A force of 7.0 N is applied horizontally and the block accelerates at 3.5 m s^{-2}. **Determine** the frictional force and its direction.

6 A 15 kg carton is being dragged along a horizontal surface by a force of 95 N. If friction amounts to 90 N, **determine** the motion of the carton.

7 When an 8 kg schoolbag is given a kick across a floor, it starts moving at a speed of 6 m s^{-1} and slides to rest in 3.0 m. **Determine** the frictional force acting.

Interpret, evaluate and communicate

8 Using examples, **evaluate** why it is sometimes necessary to increase friction.

9 **Assess** the pairs of surfaces on which friction acts during a tug of war. There may be more than one pair.

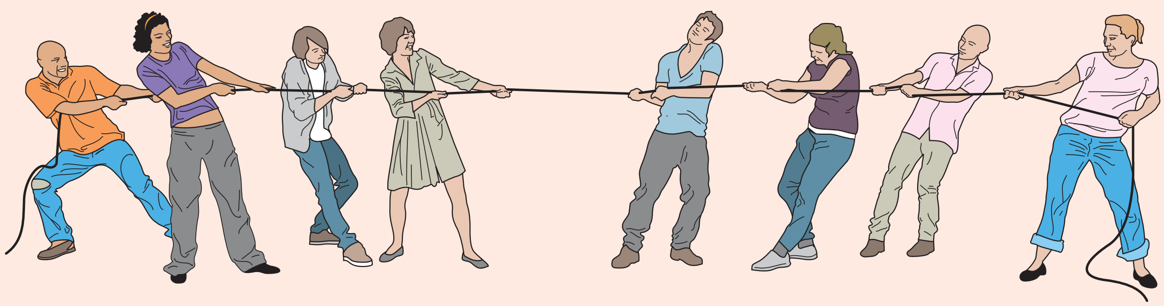

FIGURE 3 Tug of war

Check your obook assess for these additional resources and more:

» Student book questions
Check your learning 11.6

» Video
Measuring friction with a spring balance

» Video
Measuring friction with photogate

» Video worksheet
Measuring friction with a spring balance

11.7 Terminal velocity and drag forces

KEY IDEAS

In this section, you will learn about:

- drag force
- terminal velocity.

terminal velocity
speed reached when the speed of an object falling through fluid becomes constant

If you drop a rock off a cliff, it gets faster and faster as gravity causes it to accelerate toward the ground. However, as it speeds up, air resistance also increases so eventually the force upwards due to the air equals the force of gravity (down), and the rock stops accelerating and falls at a constant velocity thereafter. This is called its **terminal velocity**. 'Terminal' comes from the Latin word *terminus* meaning 'limit' or 'the end'.

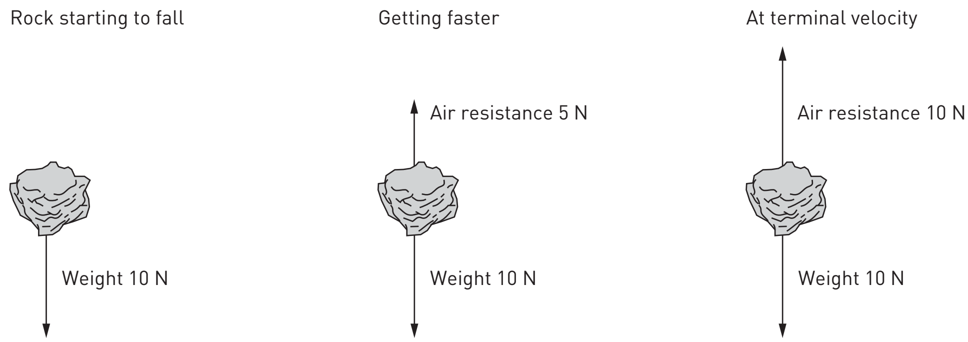

FIGURE 1 Forces acting on a rock falling freely to the ground

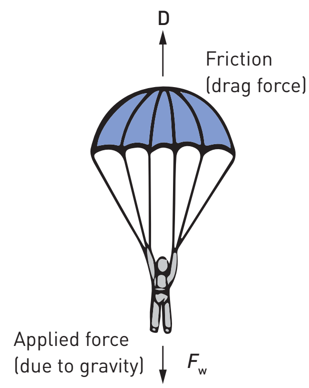

FIGURE 2 Forces acting on a parachutist

CHALLENGE 11.7

Catch while skydiving

Two skydivers are free-falling. Before their parachutes open, they try to throw a tennis ball back and forth. Propose some reasons why it won't be possible. Once their parachutes open, would it then be possible?

Without air resistance, objects would accelerate at 9.8 m s^{-2} toward the ground. In general, the frictional force between an object and the fluid medium through which it is moving is called the **drag force**.

drag force
force acting to oppose the motion of any object moving with respect to a surrounding fluid

FIGURE 3 In parachuting, air resistance opposes motion due to gravity

TABLE 1 Terminal velocity of some objects

Object	Terminal velocity ($m\ s^{-1}$)
6 kg steel shot	150
Skydiver (typical)	50
Cricket ball	40
Tennis ball	30
Rock (1 cm)	25
Basketball	20
Ping-pong ball	10
Raindrop (3 mm)	7
Insect	6
Parachutist (typical)	5

Surviving free-fall

If you are spreadeagled in air, you will free-fall for about 12 s and reach 190 km h^{-1} in about 370 m. If you fall head-first, you will reach about 300 km h^{-1} in that time.

There are some incredible anecdotes about people surviving free-fall:

- While flying in a British bomber in 1944, tail-gunner Nick Alkemade bailed out after being hit by enemy fire. He fell 5500 m without a parachute to the snow-covered ground in enemy territory. He was uninjured.
- The first person to break the sound barrier in a free-fall was Felix Baumgartner in 2012 from a height of 38 km. He fell to Earth at a supersonic speed of 1358 km h^{-1}. He deployed his parachute after four minutes and proceeded to land safely.

CHECK YOUR LEARNING 11.7

Describe and explain

1 **Explain** terminal velocity.

2 **Identify** factors that drag force depends on.

3 **Describe** how drag forces and terminal velocity relate.

4 When the upward force of air resistance on a parachutist equals their weight (down), shouldn't they be stationary? **Explain**.

5 A tennis ball is thrown vertically into the air. If air resistance is taken into account, will the time taken to travel upward equal the time coming back down? **Explain** using a free-body diagram.

Apply, analyse and interpret

6 If you dropped a marble, a big foam ball and a small foam ball (from a bean bag) together from chest height:

a **Determine** which two balls will hit the ground at the same time.

b **Explain** if these two balls would be faster or slower than the other one.

Investigate, evaluate and communicate

7 If an elephant, a human and a mouse fell from the 20th storey of a high-rise building, the elephant would splatter on impact and die, the human would be crushed and die, and the mouse would walk away. **Propose** why.

Check your obook assess for these additional resources and more:

» Student book questions
Check your learning 11.7

» Challenge
11.7 Catch while skydiving

» Weblink
Skydiving

» Weblink
Drag force and cars

CHAPTER 11

Review

Summary

11.1
- Forces can be simply divided into two types: contact and non-contact.
- A force is a push or a pull exerted on a body.
- Forces are vector quantities and can be represented in two ways: with directed line segments (arrows) or by making the quantity symbol bold or giving it an overhead arrow.
- Forces are made up of an agent (that produces the force) and a receiver (that responds to the force).

11.2
- Newton's first law states: an object maintains its state of rest or constant velocity motion unless it is acted on by an external unbalanced force.
- Inertia is the tendency of an object to resist a change to its motion.

11.3
- Newton's second law states: the acceleration of an object varies directly as the external unbalanced force applied to it and inversely proportional to its mass; $\boldsymbol{a}_{net} = \frac{\boldsymbol{F}_{net}}{m}$ or $F = ma$.

11.4
- Newton's third law states: to every action there is an equal and opposite reaction. In other words: if body A exerts a force on another body B, then body B exerts an equal and opposite force on body A.
- The force of local gravity on an object is the object's weight.

11.5
- Mass is a measure of the amount of substance in an object. It is related to weight by $F_w = mg$.
- The types of friction are static, dynamic (kinetic or sliding) and rolling.
- Friction is caused mainly by the electrostatic forces of adhesion.
- When an object moves through a fluid, it experiences a frictional or drag force (F_f).

11.6
- When a body falls freely under gravity, it begins to accelerate at g (9.8 m s^{-2}). Because of air resistance, this value slowly decreases until it reaches zero. At this speed, the object has reached terminal velocity.
- Normal force is the force exerted on a body by a surface against which it is pressed. It is always perpendicular to the surface.

Key terms

- adhesion
- agent
- applied force
- balanced forces
- contact forces
- drag force
- dynamic friction
- force
- free-body diagram
- friction
- gravitational force
- mass
- Newton's first law
- Newton's second law
- Newton's third law
- non-contact forces
- receiver
- rolling friction
- static friction
- tension
- terminal velocity
- unbalanced forces
- weight

Key formulas

Newton's second law	$\boldsymbol{a}_{net} = \frac{\boldsymbol{F}_{net}}{m}$
Relating mass to weight	$\boldsymbol{F}_w = m\boldsymbol{g}$

Revision questions

The relative difficulty of these questions is indicated by the number of stars beside each question number: ★ = low; ★★ = medium; ★★★ = high.

Multiple-choice

1 A student is sitting on a chair. One force that is acting on the student is the pull of gravity. According to Newton's third law there must be another force acting, which is:

- **A** the upward push of the chair on the student.
- **B** the downward force on the student.
- **C** the downward push of the chair on Earth.
- **D** the upward force on Earth.

2 A ball, initially at rest, is dropped in the air from a great height. Air resistance is not negligible. Which of the following graphs best shows the variation with time *t* of the acceleration *a* of the ball?

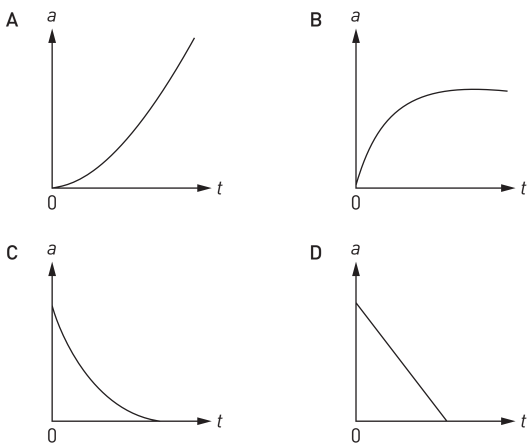

FIGURE 1 Graph options

3 Which of the following is a correct interpretation of Newton's second law of motion?

- **A** A force acting on a body is proportional to the mass of the body.
- **B** The rate of change of momentum of a body is equal to the net external force acting on the body.
- **C** The momentum of a body is proportional to the net external force acting on the body.
- **D** A force acting on a body is proportional to the acceleration of the body.

4 A cart of mass *M* is on a horizontal frictionless table.
The cart is connected to an object of weight F_g via a pulley. Which of the following is the acceleration of the cart?

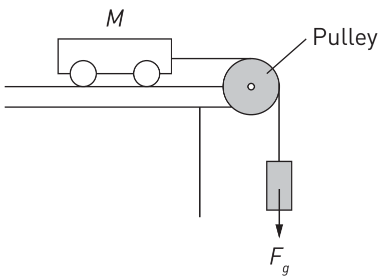

FIGURE 2 Hanging mass accelerating a cart

- **A** $\frac{M + \frac{F_g}{g}}{F_g}$.
- **B** $\frac{F_g}{M + \frac{F_g}{g}}$
- **C** $\frac{M_g}{F_g}$.
- **D** zero

5 When a car's velocity is negative and its acceleration is negative, which of the following is happening to the car's motion?

- **A** The car slows down.
- **B** The car speeds up.
- **C** The car travels at constant speed.
- **D** The car remains at rest.

Short answer

Describe and explain

★ **6** **Identify** one characteristic that gravity and magnetism have in common, and one difference.

★ **7** **Explain** why you fall forward when a moving bus comes to a halt but you move backwards when it takes off again.

★ **8** Suppose an object is travelling at constant velocity. Does this mean no forces are acting on it? **Explain**.

★★ **9** **Explain** why seat belts have spring tensioners to hold them firmly against your body instead of being loose.

★★ **10** **Calculate** the resultant force when the following forces act on the same object:

- **a** 24 N north, 18 N south, 19 N north
- **b** 6.5 N down, 9.2 N up and 7.4 N up

★★ **11** In a cathode ray tube, an electron starts from rest in the filament and experiences an unbalanced force of 8.0 femtonewtons over a distance of 20 mm. (You'll need to find the meaning of the prefix 'femto'.)

- **a** **Calculate** the electron's acceleration.
- **b** **Calculate** the electron's speed at the end of the 20 mm (starting from rest).

★★ **12** **Sketch** a diagram showing the forces acting on the block in Figure 3 and **calculate** their values.

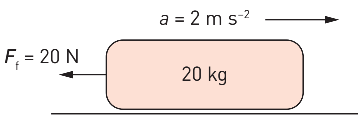

FIGURE 3 Force diagram

Apply, analyse and interpret

★ **13** **Distinguish** between mass and weight.

★ **14** **Determine** what force is necessary to uniformly accelerate:

- **a** a 6.4 kg mass at 2.4 m s^{-2} east
- **b** a 0.16 kg mass from rest to 2 m s^{-1} in 3 s
- **c** an object weighing 25 N at 9.8 m s^{-2}.

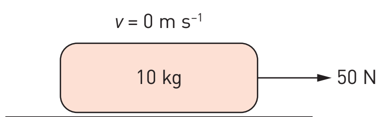

FIGURE 4 Force diagram

★★ **15** When you jump off a diving platform into a swimming pool, **consider** if you are really weightless for the short time you are in the air.

★★ **16** A wooden box of bolts has a mass of 250 kg and requires a horizontal force of 2100 N to slide it along a horizontal wooden surface at a constant speed. If the box were to be kept moving constantly at twice this speed, **determine** what force would be needed to maintain this constant speed.

★★ **17** A horizontal force of 50 N is applied to a 10 kg box resting on a horizontal surface (Figure 5). The box is not moving. **Determine** the force of friction.

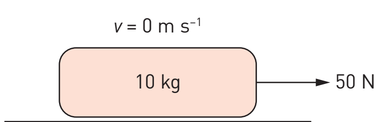

FIGURE 5 Force diagram

★★ **18** The graph in Figure 6 is an acceleration–force graph for an experiment with a loaded cart pulled by rubber bands.

- **a** **Explain** what the intercept of the graph with the force axis measures.

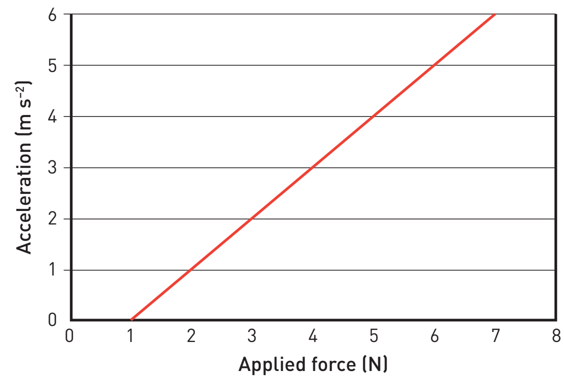

FIGURE 6 Acceleration–force graph

- **b** **Determine** what acceleration an applied 2.5 N force would produce.
- **c** **Determine** what net force would produce an acceleration of 2.0 m s^{-2} and what applied force this is equal to.
- **d** **Calculate** the mass of the loaded cart.

★★ **19** A bicycle and rider have a combined mass of 65 kg. When travelling at 5.0 m s^{-1} on a level road, the cyclist ceases to pedal and comes to rest in 255 m. **Determine** what frictional forces must have been acting on the cyclist.

★★★ **20** A cable used to pull mine cars vertically to the pit head has a breaking strain of 3 × 10^4 N. If the mine shaft is 500 m deep and a full mine car has a mass of 2500 kg, **determine**:

- **a** the maximum acceleration the mine car can reach without breaking the cable
- **b** the shortest time in which the mine car can be pulled from rest to the surface in the event of an accident.

Investigate, evaluate and communicate

★ **21** Imagine you were to drop a book that has a paper napkin resting on the top (Figure 7). **Determine** how the objects will fall.

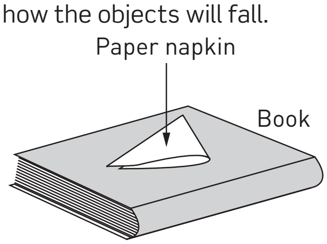

FIGURE 7 How would these objects fall?

★★ **22** The objective of a parachute is to slow the descent of a falling object in air, but modern parachutes have a hole (the apex vent) in the top, allowing air to escape.

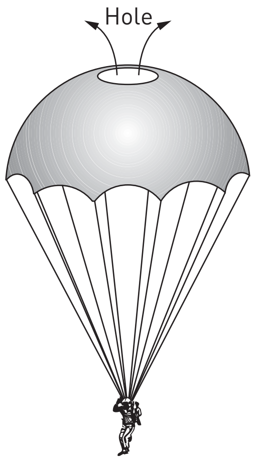

FIGURE 8 Modern parachutes have an apex vent

a **Propose** why modern parachutes are designed with an apex vent.

In the Second World War, parachutes did not have apex vents and they swung like pendulums as they descended (watch an old war movie and you'll see).

b **Explain** the physics behind this.

★★ **23** Two identical-looking foam balls are dropped off a high veranda, but a brass mass has been stuck inside one of the balls. **Propose** which ball will hit the ground first.

★★ **24** A piece of paper is scrunched up tightly into the size of a golf ball. When you drop the scrunched paper and the golf ball simultaneously, **propose** whether they will hit the ground together or one after the other.

★★ **25** **Comment** on this statement: 'Mass is the property of one object alone, whereas weight is the interaction of two objects.'

★★ **26** 'When balanced forces act on an object, the object must be at rest.' **Evaluate** this statement.

★★ **27** During an experiment, a frictionless trolley was subjected to a single force whose magnitude could be varied. Assume the friction was negligible. The acceleration from various forces was measured and the results tabled as shown in Table 1.

TABLE 1

Force (N)	5	10	15	20	25
Acceleration (m s^{-2})	1.5	3.0	4.5	6.0	7.5

a **Sketch** a graph of the results.

b **Determine** the mass of the trolley.

c **Propose** how the shape of the graph would have changed if friction was present.

★★ **28** An experiment was conducted to find the relationship between force, mass and acceleration. A stretched rubber band was used to provide constant force on a trolley to which different masses were added (see Figure 9). The trolley was released from rest and timed to move 50.0 cm.

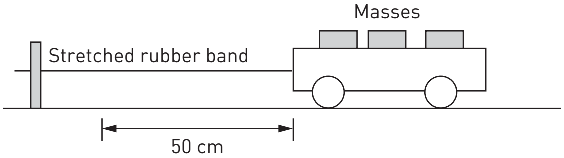

FIGURE 9 Experiment set-up

A student made the following notes:

'When the trolley had no masses on it, it took 2.00 s. With 300 g added it took 2.40 s and with 900 g added it took 2.60 s. I measured the mass of the trolley by itself and it was 700 g.'

a **Construct** a data table to show the results.

b **Solve** the acceleration for each trial and add this to the table.

c **Sketch** a graph of total mass (horizontal axis) versus acceleration.

d **Identify** the relationship suggested by this graph.

e Use Newton's second law of motion to **calculate** the force provided by the rubber band in each case and add this information to the table.

The student was supposed to have measured the time with 600 g added but forgot.

f **Propose** what acceleration the student would have calculated.

g **Determine** how long the trolley would have taken to cover the 50 cm in this case.

h **Discuss** one factor that would have had to remain constant during the entire experiment.

Check your obook assess for these additional resources and more:

- Student book questions
  Chapter 11 revision questions
- Revision notes
  Chapter 11
- assess quiz
  Auto-correcting multiple choice quiz
- Flashcard glossary
  Chapter 11

CHAPTER 12

Momentum

Ballet, bullets, bombs, baseball, boxing and binary stars all have something in common – they all involve the combination of mass and velocity.

OBJECTIVES

→ Define the terms momentum and impulse.
→ Recall the principle of conservation of momentum.
→ Solve problems involving momentum, impulse, the conservation of momentum and collisions in one dimension.
→ Determine and interpret the area under a force–time graph.

Source: *Physics 2019 v1.2 General Senior Syllabus Queensland Curriculum & Assessment Authority*

PRACTICALS

SUGGESTED PRACTICAL	**12.1** Elastic collision between trolleys – momentum conservation

FIGURE 1 In a grand jeté, a ballet dancer looks as though they glide through the air. The dancer does this by moving the position of their legs into a split position at the top of the jump. It is an example of conservation of momentum.

MAKES YOU WONDER

In this chapter we will be examining some aspects of momentum that will help to answer questions such as:

→ Would you rather be hit by a 1 g ball bearing travelling at 100 m s^{-1} or by a 100 g ball travelling at 1 m s^{-1}?

→ Which would hurt more – being tackled by a lightweight footballer travelling at high speed or by a big, heavy footballer travelling at low speed?

→ In a collision, which is more important – mass or speed?

→ When a target is hit by a bullet, can it ever move towards the shooter (as people have claimed happened in the assassination of United States President Kennedy)?

→ Which would be the worse car crash: two cars travelling at 50 km h^{-1} colliding head-on, or one car travelling at 100 km h^{-1} hitting a stationary car?

12.1 Momentum and impulse

KEY IDEAS

In this section, you will learn about:

- momentum
- change in momentum
- the rate of change in momentum
- impulse
- force–time graphs.

momentum
a vector quantity, the product of an object's mass and its velocity

We are told that **momentum** is the product of mass and velocity ($m \times v$), but why is it not some other combination, such as $m \times v^2$ or $m^2 \times v$? Newton showed that in any interaction where two or more bodies are involved, momentum is conserved – it doesn't change. Newton never defined momentum mathematically, but it is clear he was referring to the product of mass and velocity (Latin *movimentum*, from *movere* meaning 'to move').

$$\textbf{Momentum} = \text{mass} \times \text{velocity}$$

$$\boldsymbol{p} = m\boldsymbol{v}$$

Note the following about momentum:

- It is a vector quantity because velocity is a vector quantity.
- The direction of the momentum vector is the same as the direction of the velocity vector.
- Momentum is a useful quantity to describe the motion of an object.
- Momentum has the symbol p.
- The unit of momentum does not have a special name. The unit is kg m s^{-1} and is the same as N s, so this is often used.

Students often ask, 'Why is momentum given the symbol p?' The answer has been lost, but nevertheless it was coined by William Hamilton in 1833 in his development of Newton's laws.

WORKED EXAMPLE 12.1A

Calculate the momentum of a 2 kg bowling ball travelling at 8 m s^{-1} south.

SOLUTION

$\boldsymbol{p} = m\boldsymbol{v} = 2 \times 8 = 16$ kg m s^{-1} south

(Note: you must include a direction.)

Total momentum

total momentum
the vector sum of individual momenta

Two or more objects can make a 'system', and we can calculate their **total momentum** by adding their independent momentum values together.

$$\boldsymbol{p}_{total} = \Sigma\boldsymbol{p} = \boldsymbol{p}_1 + \boldsymbol{p}_2 \ldots + \boldsymbol{p}_n$$
$$= \Sigma m\boldsymbol{v} = m_1\boldsymbol{v}_1 + m_2\boldsymbol{v}_2 \ldots + m_n\boldsymbol{v}_n$$

SUGGESTED PRACTICAL

12.1 Elastic collision between trolleys – momentum conservation
Go to your obook assess »

WORKED EXAMPLE 12.1B

Two billiard balls roll toward each other. They each have a mass of 0.3 kg. Ball A is moving at 1 m s^{-1} to the right, while ball B is moving at 0.8 m s^{-1} to the left. Calculate the total momentum of the system.

SOLUTION

Call the direction to the right positive (+).

$$\boldsymbol{p}_A = m_A \boldsymbol{v}_A = 0.3 \times (+1) = +0.3 \text{ kg m s}^{-1}$$

$$\boldsymbol{p}_B = m_B \boldsymbol{v}_B = 0.3 \times (-0.8) = -0.24 \text{ kg m s}^{-1}$$

$$\boldsymbol{p}_{total} = \boldsymbol{p}_A + \boldsymbol{p}_B = +0.3 \text{ kg m s}^{-1} + (-0.24) \text{ kg m s}^{-1} = 0.06 \text{ kg m s}^{-1} \text{ (positive, so to the right)}$$

Change in momentum

As you saw with 'changes' in earlier work, a change means final minus initial. The same is true of **change in momentum**.

Change in momentum = final momentum − initial momentum

$$\Delta \boldsymbol{p} = \boldsymbol{p}_f - \boldsymbol{p}_i$$

$$\Delta(m\boldsymbol{v}) = m\boldsymbol{v} - m\boldsymbol{u}$$

change in momentum
the final momentum minus the initial momentum

WORKED EXAMPLE 12.1C

What is the change in momentum when an object of mass 2 kg travelling at 5 m s^{-1} east is accelerated to 7 m s^{-1} east?

SOLUTION

Change in momentum = final momentum – initial momentum

Final momentum: $p_f = mv = 2 \times 7 = 14$ kg m s^{-1} east

Initial momentum: $p_i = mu = 2 \times 5 = 10$ kg m s^{-1} east

$\Delta p = p_f - p_i$

To subtract the initial momentum from the final momentum, change the direction of the initial momentum to the opposite (that is, from east to west), and add it to the final momentum by putting the vectors head to tail (Figure 1).

Change in momentum = 4 kg m s^{-1} east

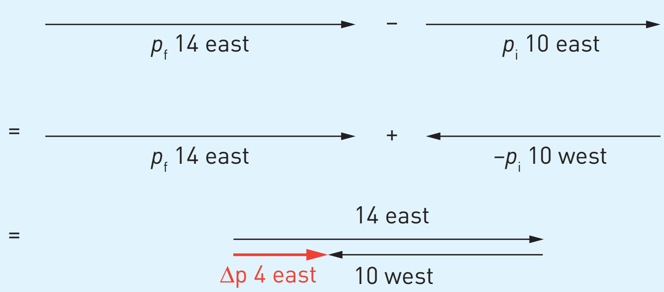

FIGURE 1 Determining change in momentum

Study tip

Some more changes in momentum worked examples can be found on your obook assess.

Impulse

In 1687, Newton originally wrote his second law as, 'the force on an object equals the rate of change in momentum':

$$\text{Force} = \frac{\text{change in momentum}}{\text{time}}$$

$$\boldsymbol{F} = \frac{mv - mu}{t} = \frac{\Delta \boldsymbol{p}}{t}$$

Hence, the rate of change of momentum is equal to the external force causing the change. This can be rearranged as:

$$\Delta p = \boldsymbol{F}t$$

$$\text{Change in momentum} = \text{impulse}$$

impulse
a vector quantity defined as the change in momentum of an object, which is the product of a force and the time interval over which the force acts

The product $\boldsymbol{F}t$ is called the **impulse** (Latin *pulsus* = 'to beat' or 'drive') and is given the symbol $\boldsymbol{J}$. It is a vector quantity. Impulse depends on the size of the force and for how long it is applied. It is also equal to the change in momentum. The unit for impulse is newton second (N s), which is the same as kg m s^{-1}.

Force–time graphs

force–time graph
depicts the force acting on an object as a function of time, with the area underneath being equal to the impulse

It is useful to see how the force applied to an object changes during the course of some interaction, such as hitting a nail with a hammer or someone jumping in the air. Most situations involve forces that do not remain constant. We can use a **force–time graph** to show the force changes. The area under such a graph is $F \times t$, which is equal to impulse (Figure 2).

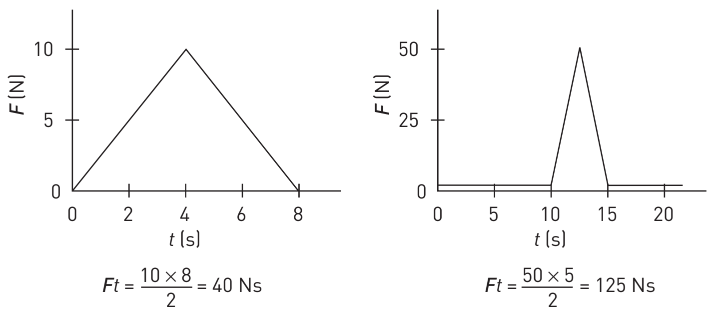

FIGURE 2 Force-time graphs allow impulse to be calculated.

WORKED EXAMPLE 12.1D

Figure 3 is a graph showing how force varies with time as a stationary 57 g tennis ball is struck by a racquet.

Calculate the:

a impulse

b final velocity of the ball.

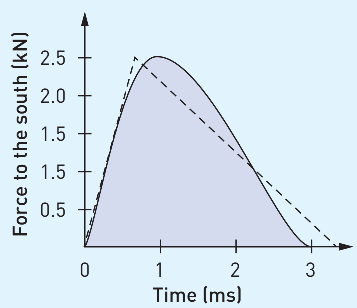

FIGURE 3 The force exerted on a tennis ball during a serve can be represented graphically.

SOLUTION

a The area under the graph is a measure of $F \times t$, which is the impulse. In this case, the impulse is approximated by the dotted triangle in Figure 3:

$$A = \frac{b \times h}{2} = \frac{3.2 \times 10^{-3} \times 2.5 \times 10^{3}}{2}$$

$$= 4.0 \text{ N s (south)}$$

b Impulse = $\Delta \boldsymbol{p}$

$$Ft = m\boldsymbol{v} - m\boldsymbol{u}$$
$$= m(\boldsymbol{v} - \boldsymbol{u})$$
$$4.0 = 0.057(\boldsymbol{v} - 0)$$
$$\boldsymbol{v} = 70\ \text{m s}^{-1}\ \text{south}$$

CHECK YOUR LEARNING 12.1

Describe and explain

1 **Describe** what momentum is.

2 **Explain** what is meant by a change in momentum.

3 **Explain** what a force–time graph measures.

4 **Describe** impulse.

5 **Calculate** the magnitude of the momentum of the following moving objects:

a a 1000 g bowling ball moving at 1.6 m s^{-1}

b a 2.0 tonne car moving at 15 m s^{-1}

c Earth in its journey around the Sun. (Earth's mass is 6×10^{24} kg and its average radius of orbit is 1.5×10^{11} m)

6 A 900 kg car is travelling east at a velocity of 40 km h^{-1} when it is approached by a 290 kg motorbike travelling west at a velocity of 90 km h^{-1}. **Calculate** the total momentum of the system.

7 A proton of mass 1.67×10^{-27} kg is accelerated from 2×10^4 m s^{-1} to 9×10^5 m s^{-1}. **Calculate** the change in momentum.

Apply, analyse and interpret

8 A force of 3 millinewton acts on an electron for 0.15 seconds. Determine the impulse imparted on the electron.

9 A mass of 2.4 kg is moving at 6.0 m s^{-1} north.

a **Determine** how long, and in what direction, a frictional force of 5.6 N must act to bring it to rest.

b **Calculate** the impulse acting on the object.

10 A tennis ball is struck by a racquet as shown by the graph (Figure 4).

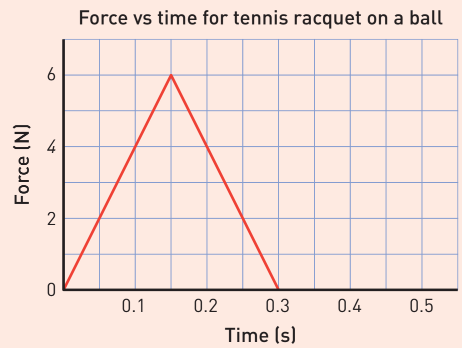

FIGURE 4 Force-time graph

Determine the:

a impulse given to the ball

b change in momentum of the ball.

11 **Consider** Figure 5 which shows a force–time graph for an object over 10 s.

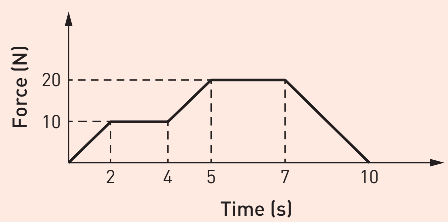

FIGURE 5 Force-time graph

a **Calculate** the impulse imparted to the object over the whole 10 seconds.

b **Determine** the greatest impulse given.

Check your obook assess for these additional resources and more:

» **Student book questions**
Check your learning 12.1

» **Suggested practical**
12.1 Elastic collisions between trolleys-momentum conservation

» **Video**
Force-time graph

» **Increase your knowledge**
Worked examples of changes in momentum

12.2 Conservation of linear momentum

KEY IDEAS

In this section, you will learn about:

+ the law of conservation of momentum.

When you throw a ball, shoot a bullet or give someone a push, you tend to move backward. Newton's third law of motion explains that action and reaction were equal and opposite forces. When these opposing forces act on each other for the same time, we can say that the change in momentum of object A is equal and opposite to the change in momentum of object B. In other words, if we add together the changes in momentum for both objects we get zero.

Alternatively, we can say that for two objects colliding in an isolated system, the total momentum before and after the collision is equal. This is called the **law of conservation of momentum**. In a closed system, the change in momentum is zero ($\Delta p = 0$).

law of conservation of momentum states that for two objects colliding in an isolated system, the total momentum before and after the collision is equal

$$\Sigma m v_{\text{before}} = \Sigma m v_{\text{after}}$$

Examples of the concept and uses of the law of conservation of momentum are common in everyday life, but often they need pointing out to become obvious. The two most common interactions we can study are explosions and collisions.

Explosions

explosion when a single object separates into two or more fragments

An **explosion** can be thought of as a single object separating into two or more fragments. The word 'explode' was first used to mean 'burst with destructive force' in the nineteenth century when a mathematical treatment of explosions became necessary.

Some familiar explosions are:

- a bomb blowing into fragments
- a bullet shot out of a gun
- water streaming out of a hose
- an alpha particle ejected out of a nucleus
- blood pumping out of your heart.

Consider a 10 kg bomb at rest that explodes into two fragments (Figure 1). If a 4 kg piece (m_1) travels west at 15 m s^{-1} (v_1), then the 6 kg piece (m_2) would have moved in the opposite direction (at a speed v_2). As there was no external unbalanced forces acting on the bomb (all forces were internal), we have a closed system and there would be no change in the total momentum of the system. This is the law of conservation of momentum.

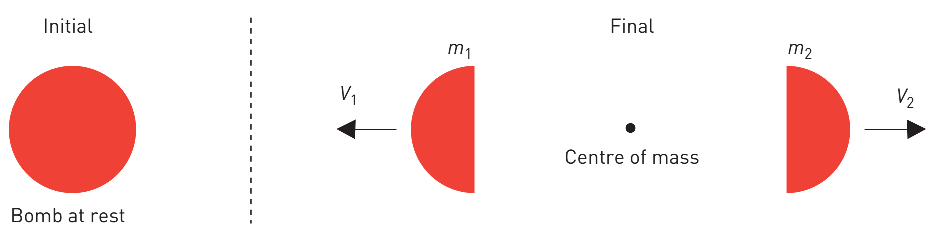

FIGURE 1 Bomb exploding away from the centre of mass

$$\boldsymbol{p}_{\text{before}} = \boldsymbol{p}_{\text{after}}$$
$$\Sigma m\boldsymbol{v}_{\text{before}} = \Sigma m\boldsymbol{v}_{\text{after}} \text{ (law of conservation of momentum)}$$
$$(m_1 + m_2)\boldsymbol{u} = m_1\boldsymbol{v}_1 + m_2\boldsymbol{v}_2$$
$$10 \times 0 = 4 \times 15 + 6 \times \boldsymbol{v}_2$$
$$\boldsymbol{v}_2 = -10 \text{ m s}^{-1} \text{ (the negative sign means east)}$$

WORKED EXAMPLE 12.2A

A boy on roller-skates is travelling along at 8 m s^{-1}. He has a mass of 60 kg and is carrying his schoolbag of mass 10 kg. He throws the bag directly forward at 20 m s^{-1} relative to the ground. Calculate the boy's speed after the 'explosion'.

SOLUTION

The boy and the bag have initial velocities in the positive direction. The final velocity of the bag is also positive.

$$\boldsymbol{p}_{\text{before}} = \boldsymbol{p}_{\text{after}}$$
$$(m_1 + m_2)\boldsymbol{u} = m_1\boldsymbol{v}_1 + m_2\boldsymbol{v}_2$$
$$(60 + 10) \times 8 = 60 \times \boldsymbol{v}_1 + 10 \times 20$$
$$560 = 60 \times \boldsymbol{v}_1 + 200$$
$$\boldsymbol{v}_1 = +6 \text{ m s}^{-1}$$

The positive direction means that the boy would continue to move forward.

Relationships such as this can be applied to all sorts of explosions. However, cases in which the bodies explode in a straight line (one dimension) are not that common. Explosions in two dimensions are not dealt with in this text.

Collisions

The Wolfe Creek Crater in Western Australia is a result of a meteor collision with Earth 300 000 years ago. Travelling at about 15 km s^{-1}, the 100 000 tonne chunk of iron would have exploded on impact with Earth and turned to vapour (along with huge quantities of the quartzite rock underneath).

In everyday language, a **collision** occurs when objects hit each other. This suits our purpose in physics too.

collision
when two or more objects hit each other

Some familiar collisions are:

- a meteor crashing into Earth
- cars running into each other
- a billiard ball being struck by a cue
- gas molecules bouncing off each other.

FIGURE 2 Wolfe Creek Crater in Western Australia is the result of a meteor collision with Earth. It has been known to the local Djaru people as *Kandimalal* for thousands of years.

Types of collisions

elastic collision a collision in which kinetic energy is conserved

inelastic collision a collision in which total kinetic energy is not conserved

Collisions can be grouped into two types:

- **Elastic collisions** – where kinetic energy is conserved; includes some collisions in which objects collide and bounce off each other (such as gas molecules or billiard balls).
- **Inelastic collisions** – where kinetic energy is not conserved; includes collisions in which objects collide and remain bound to each other (such as a bullet in a target).

Elastic collisions

Consider a collision between two masses m_1 and m_2 with initial velocities u_1 and u_2 respectively (Figure 3).

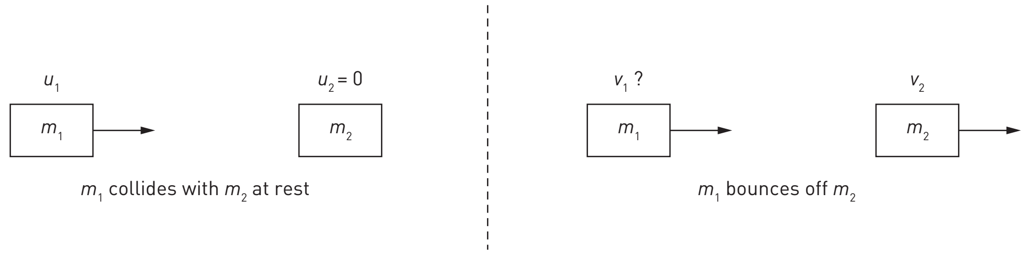

FIGURE 3 Diagram of a collision between two masses showing before (left) and after (right)

For the law of conservation of momentum to hold, the momentum before the collision must equal the momentum after the collision:

$$\Sigma m\boldsymbol{v}_{\text{before}} = \Sigma m\boldsymbol{v}_{\text{after}}$$
$$m_1\boldsymbol{u_1} + m_2\boldsymbol{u}_2 = m_1\boldsymbol{v_1} + m_2\boldsymbol{v}_2$$

WORKED EXAMPLE 12.2B

A cart with a mass of 2 kg travelling at 6 m s^{-1} collides with another cart of mass 0.4 kg travelling in the same direction at 2 m s^{-1}. It bounces off, as shown in Figure 4. After impact, the 2 kg cart travels at 3 m s^{-1} in the same direction. Calculate the velocity of the 0.4 kg cart after the collision.

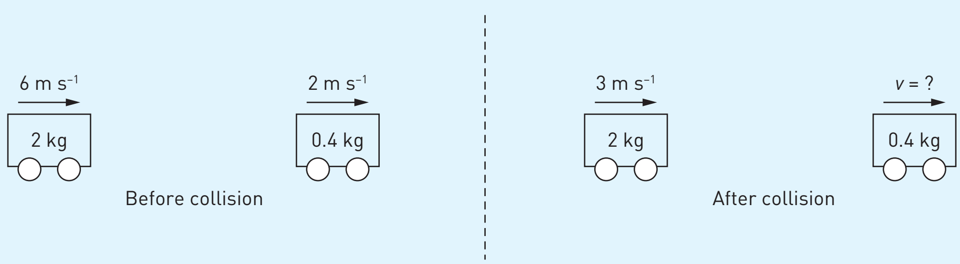

FIGURE 4 In this collision, the second cart bounces off the first cart.

SOLUTION

$$\Sigma m\boldsymbol{v}_{\text{before}} = \Sigma m\boldsymbol{v}_{\text{after}}$$
$$m_1\boldsymbol{u}_1 + m_2\boldsymbol{u}_2 = m_1\boldsymbol{v}_1 + m_2\boldsymbol{v}_2$$
$$2 \times 6 + 0.4 \times 2 = 2 \times 3 + 0.4 \times \boldsymbol{v}_2$$
$$\boldsymbol{v}_2 = +17 \text{ m s}^{-1}$$

The positive sign indicates the cart is moving in the same direction as before.

Inelastic collisions

When objects stick together or are joined together, they are said to be coupled (Latin *copulare* = 'to bond'). In a collision where the objects become coupled, the law of conservation of momentum still holds but the mass of the combined body after the collision is equal to the sum of the individual masses of the colliding bodies.

Some examples of inelastic (sometimes called coupled) collisions are:

- an arrow sticking into its target
- two cars colliding head-on.

CHALLENGE 12.2

What knocks the block?

A superball is tied to a 1.5 m string and suspended vertically from a hook. It is pulled back and allowed to strike a wooden block standing on the floor. The experiment is repeated with a lump of plasticine of the same mass in place of the ball. One knocks the block over, one doesn't. Which is which and why?

WORKED EXAMPLE 12.2C

A supermarket trolley loaded with shopping has a mass of 60 kg. It rolls across the floor at 4 m s^{-1} and collides with an empty trolley of mass 25 kg, which was stationary. They become fastened together and roll on as one. Calculate the magnitude of the velocity of the two trolleys when locked together.

SOLUTION

$$\Sigma m v_{before} = \Sigma m v_{after}$$
$$m_1 u_1 + m_2 u_2 = m_1 v_1 + m_2 v_2$$
$$m_1 u_1 + m_2 u_2 = (m_1 + m_2) v \text{ (as } v_1 = v_2)$$
$$60 \times 4 + 25 \times 0 = 85 \times v$$
$$v = 2.8 \text{ m s}^{-1}$$

Practical use of inelastic collisions

One way of measuring bullet speeds is to make use of an inelastic collision. If an air-rifle pellet is shot into a soft absorbent target (such as a toilet roll) that is attached to a linear airtrack glider (very low friction), the glider moves away under the impact of the pellet. By measuring the time it takes the glider to move a specified distance (50 cm in Figure 5), the velocity of the glider can be determined. This data can be used to calculate the velocity of the pellet.

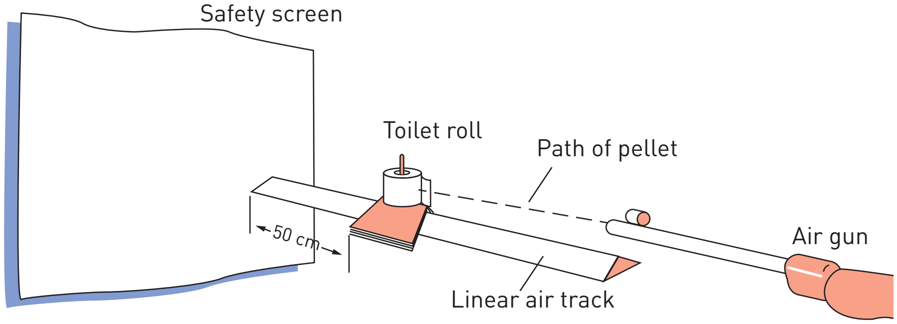

FIGURE 5 Measuring the velocity of an air-rifle pellet in the laboratory

FIGURE 6 An air rifle being fired at a target

WORKED EXAMPLE 12.2D

When a 0.45 g air-rifle pellet is fired into a target attached to a glider on a frictionless linear air track, the glider moves 50 cm in 3.8 seconds. Calculate the magnitude of the velocity of the pellet. The glider and target have a combined mass of 643 g.

SOLUTION

Mass of pellet = 0.45 g = 4.5×10^{-4} kg

Combined mass = 643 g = 0.643 kg

$$\text{Velocity of glider} = \frac{s}{t} = \frac{0.5}{3.8} = 0.13\ \text{m s}^{-1}.$$

$$\Sigma m v_{before} = \Sigma m v_{after}$$

$$m_{pellet} \times u_{pellet} = m_{target} \times v_{target}$$

$$u_{pellet} = \frac{m_{target} \times v_{target}}{m_{pellet}} = \frac{0.643 \times 0.13}{4.5 \times 10^{-4}}$$

$$= 186\ \text{m s}^{-1}$$

Note: the final mass of the glider and target should include the mass of the embedded pellet but, as it is negligible, it can be ignored in this case. If the mass of the embedded object was large, it would have to be included.

A device called a ballistic pendulum can be used for measuring the speed of high-speed bullets. This will be described in Chapter 13.

CHECK YOUR LEARNING 12.2

Describe and explain

1 **Explain** momentum.

2 **Describe** what is meant by the law of conservation of momentum.

3 **Recall** an example for:
   a an elastic collision
   b an inelastic collision.

4 Two children at rest push off from each other in a swimming pool. The first child, with a mass of 50 kg, moves east at 1.5 m s^{-1} and the second child, who has a mass of 45 kg, moves to the west. **Calculate** the second child's velocity.

5 A girl of mass 50 kg is stationary on an ice rink. She throws a 1.0 kg parcel horizontally at 5.0 m s^{-1}. **Calculate** the velocity at which the girl moves.

6 **Consider** a collision of two lawn bowls each weighing 300 g. Ball A is at rest and ball B is moving towards it with a speed of 2 m s^{-1}. After the balls collide, ball B comes to an immediate stop and ball A moves off. **Demonstrate** mathematically that the final velocity of ball A is 2 m s^{-1}.

Apply, analyse and interpret

7 A jet flies at a speed of 355 m s^{-1}. The pilot fires a missile forward off a mounting at a speed of 750 m s^{-1} relative to the ground. The respective masses of the jet and the missile are 6000 kg and 60 kg. **Determine** the new speed of the jet immediately after the missile has been fired.

8 Two carts, one of mass 0.6 kg and the other of mass 0.8 kg, are moving north along a smooth horizontal surface with speeds of 4 m s^{-1} and 2 m s^{-1} respectively, as shown in Figure 7. After the collision, the 0.6 kg mass continues to travel north but with a speed of 1.2 m s^{-1}. **Determine** the speed of the 0.8 kg mass.

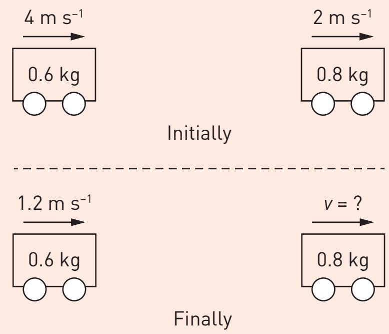

FIGURE 7 Collision diagram

Investigate, evaluate and communicate

9 A very lightweight boat 24 m long with a mass of 30 kg lies still on a quiet pond. A 90 kg man walks from bow (front) to stern. **Determine** how far the boat moves relative to the pond.

10 A 0.41 g air-rifle pellet is fired into a target made up of a 170 g toilet roll attached to a glider of 350 g. The target slides along a linear air track a distance of 50 cm in 2.8 s (refer to Figure 5, p. 343).
   a **Calculate** the velocity of the pellet.
   b **Propose** what additional information you would need to calculate the recoil speed of the air rifle.

11 Shooters who want to reduce the recoil of their rifles use a variety of anti-recoil devices. The simplest is to vent the exhaust gases out sideways instead of leaving them trapped in the barrel. One effective method involves drilling a hole in the rifle butt (the wooden shoulder piece) and inserting a rod of steel about 2 cm in diameter. Better still, inventive shooters use a length of steel water pipe three-quarters filled with mercury and capped. **Assess** how this helps.

Check your obook assess for these additional resources and more:

» Student book questions
Check your learning 12.2

» Challenge
12.2 What knocks the block?

» Video
Momentum explosions

» Weblink
Wolfe Creek Crater – meteor collision

SCIENCE AS A HUMAN ENDEAVOUR

12.3 Car collisions

KEY IDEAS

In this section, you will learn about:

+ applications for Newton's laws of motion and conservation of momentum for road safety and technology.

The safety of passengers in a car during a collision has drastically improved over time. Knowledge of forces and motion has led to improvements in car safety through the development and use of devices such as seatbelts, crumple zones and air bags.

Passenger safety also depends on the time interval in which the moving car is brought to a stop. The slower this happens, the smaller the force needed and the smaller the potential damage. To reduce the force of impact, we have to increase the time it takes.

Most of these features are based on the principle that the longer it takes for your body to come to rest, the smaller the force your body has to stand. While the change in momentum is usually the same no matter how you crash, it is better to suffer a small force for a long time than a large force for a short time.

The same principle applies when you catch a water balloon. To stop it bursting, you need to catch the balloon in mid-air and then bring it to a stop slowly by allowing your hands to travel with it before reducing its momentum down to zero. There is no way around the fact that you are attempting to bring about a substantial momentum change – a change equal in value to the momentum of the object in movement. Nevertheless, by increasing the stopping time you reduce the effects of force of the balloon to less than the tensile strength of the balloon (the force needed to break the rubber).

Crumple zones

The main way car occupants are kept safe is by making the front and rear of cars collapsible. These 'crumple zones' must not be too hard or too soft. They must progressively collapse so that the time of the collision is made as long as possible.

Prior to the mid-1950s, engineers believed the stronger the structure, the safer the car. Early car designs saw rigid bodies that were very resistant during an accident and didn't allow too much crumpling. As a result, all the forces were transferred to the occupants – most of the time being fatal. It wasn't until the mid-1950s that the first crumple zones were implemented on vehicles.

Studies have shown that the different bones of a human body can withstand various forces before they break; for example, skull = 2300 N, rib = 3300 N and femur (upper leg) = 4000 N. A car collision where the driver comes to rest in 0.1 s would be sufficient to fracture the three types of bones mentioned. However, if the collision took 1.0 s then none of those bones would be broken. Even if the car did come to rest in 0.1 s, there are other ways of extending this time for the occupants – by the use of air bags and seatbelts.

FIGURE 1 In this head-on collision, the passengers would have experienced lower forces because of the crumple zones

Air bags

Air bags increase the time taken for the occupant's head to decelerate from impact speed to zero. The inflated bag cushions the person's head and brings it to rest over a longer time (perhaps 100 ms, which is 0.100 s). Typically, the air bag sensor reacts to the collision after 20 ms, and after a further 5 ms the chemicals in the bag are ignited. The released gas takes another 10 ms to inflate the bag. It is then another 25 ms before the head makes contact with the bag, so the inflated bag is ready and waiting when the head comes crashing in to it.

The person's head continues in a straight line after the car first hits the stationary object. The car begins to decelerate as the crumple zones do their job, but the head is not a part of the car so it keeps moving forward at its initial speed (for example, 60 km h^{-1}) in accordance with Newton's first law. By the time the head strikes the air bag (at 60 ms) the car has slowed to just a few kilometres per hour, and by 110 ms the car has stopped moving.

Combining safety strategies

A combination of crumple zones, air bags and seatbelts contribute towards occupant safety in the event of a car crash. In all cases, they do this by extending the stopping distance and stopping time of the human body to values that are no longer life-threatening. If you increase the impact speed to 100 km h^{-1}, some of these values become borderline in preventing injury.

Given these safety features, you would think that crash deaths should have been reduced to zero over the past 50 years. However, road safety experts suggest that some drivers are adopting more risky behaviours as they believe the safety features will protect them. The physics of a car crash doesn't support this.

CHECK YOUR LEARNING 12.3

Describe and explain

1 **Explain** the purpose of a crumple zone.

Apply, analyse and interpret

2 **Describe** the benefits of modern car safety features compared with cars in the 1950s. **Consider** your understanding of force and momentum.

3 A 1400 kg VW Beetle sedan is travelling at 20 m s^{-1} and crashes into a power pole. The car comes to rest in 0.15 s. **Determine** the:
- a change in momentum
- b acceleration of the car
- c impulse
- d force of the impact by the car on the power pole
- e force by the pole on the car.

4 A 3.300 tonne Landcruiser is filmed by traffic cameras crashing into a solid barrier. The crumple zone of the car is pushed back 0.9 m and the time (from the video footage) from the moment of impact to the car becoming stationary is 0.110 seconds. The driver said she was not speeding and was on the 60 km h^{-1} limit.
- a **Determine** the:
  - i acceleration of the car during the crash
  - ii impact speed
  - iii change in momentum
  - iv force of the impact.
- b **Comment** on whether the car was over or under the 60 km h^{-1} speed limit.

Check your obook assess for these additional resources and more:

- » **Student book questions** Check your learning 12.3
- » **Increase your knowledge** Science as a human endeavour: momentum in sports and forensics
- » **Weblink** Car crashes
- » **Weblink** Surviving car crashes

CHAPTER 12

Review

Summary

12.1
- The product of mass and velocity is the vector quantity called momentum: $p = mv$. The direction of momentum is the same as the direction of velocity.
- The product Ft is called the impulse.
- The area under a force–time graph is the impulse and is measured in newton second (Ns)

12.2
- The law of conservation of momentum states that for a closed, isolated system, the momentum before an interaction equals the momentum afterwards.
- Momentum is conserved in explosions and collisions.
- Collisions can be classed as elastic collisions or inelastic collisions.
- Collisions can be analysed using vector processes.
- Knowledge of forces and motion has led to improvements in car safety through the development and use of devices such as seatbelts, crumple zones and air bags.

Key terms

- change in momentum
- collision
- elastic collision
- explosion
- force–time graph
- impulse
- inelastic collision
- law of conservation of momentum
- momentum
- total momentum

Key formulas

Law of conservation of momentum	$\sum m v_{\text{before}} = \sum m v_{\text{after}}$
Momentum	$p = mv$

Review questions

The relative difficulty of these questions is indicated by the number of stars beside each question number: ★ = low; ★★ = medium; ★★★ = high.

Multiple choice

1 A cannon fires a cannonball with an initial momentum of 5000 kg m s^{-1} to the right.

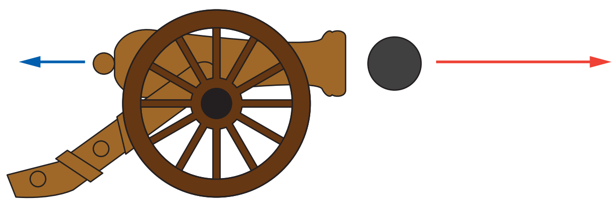

FIGURE 1 A cannon firing a cannonball

The momentum of the cannon after it fires the ball is:

A 5000 kg m s^{-1} to the right.
B 5000 kg m s^{-1} to the left.
C zero.
D 2500 kg m s^{-1} to the right.

2 Stationary skateboarder A with a mass of 50 kg pushes stationary skateboarder B with a mass of 75 kg. After the push, skateboarder B moves with a velocity of 2 m s^{-1} to the right. The velocity of skateboarder A is:

A 3 m s^{-1} to the left.
B 2 m s^{-1} to the left.
C 1 m s^{-1} to the right.
D 3 m s^{-1} to the right.

3 Two carts of different mass *m* and *M* are connected by a spring. They are pushed together such that the spring is compressed.

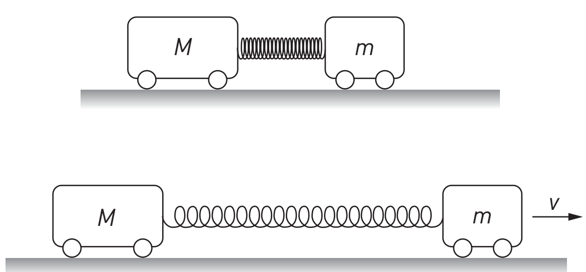

FIGURE 2 Two carts connected by a spring

After the carts are released, the cart of mass *m* moves with velocity $\boldsymbol{v}$. The change in the momentum of mass *M* is

A $m\boldsymbol{v}$.
B $-m\boldsymbol{v}$.
C $M\boldsymbol{v}$.
D $-M\boldsymbol{v}$.

4 A cannon fires a cannonball and recoils backward. Which of the following statements is true about the cannon recoil?

A Cannon recoil happens because the energy of the system is conserved.
B Cannon recoil happens because the energy of the system is increased.
C Cannon recoil happens because the momentum of the system is not conserved.
D Cannon recoil happens because the momentum of the system is conserved.

5 An 80 kg diver jumps off a moving boat. The boat has a mass of 400 kg and moves at a constant velocity of 2 m s^{-1}. If the diver jumps with a velocity of 3 m s^{-1} in the opposite direction to the initial velocity of the boat, the velocity of the boat after the jump is:

A 2 m s^{-1}.
B 3 m s^{-1}.
C 4 m s^{-1}.
D 6 m s^{-}.

Short answer

Describe and explain

★ 6 **Explain** in terms of impulse how the crumple zone on a car works.

★ 7 **Explain** why it is not feasible to use real people in crash testing.

★ 8 **Explain** how the law of conservation of momentum applies to an inflated party balloon that is let go and whizzes around the room.

★ 9 **Calculate** the momentum of a:

a cricket ball of mass 160 g moving at 12.5 m s^{-1} east
b billiard ball of mass 200 g moving at 8.5 m s^{-1} N35°E
c 100 kg footballer moving with a velocity of 8 m s^{-1} north.

★ 10 An alpha particle of mass 7×10^{-27} kg is accelerated from 5×10^{3} m s^{-1} to 2×10^{4} m s^{-1}. **Calculate** the change in momentum.

★★ **11** When running, **explain** if you transfer momentum to the Earth.

★★ **12** When you drop a book, the book increases in momentum, therefore something must lose momentum so the conservation law is obeyed. **Describe** what loses momentum.

★★ **13** **Explain** how the conservation of momentum applies to a tennis ball bouncing up off the floor.

★★ **14** **Explain** whether impulse can ever be zero, even when the force is not zero.

Apply, analyse and interpret

★ **15** When a 1545 kg Ford Falcon ute travelling at 15 m s^{-1} comes to rest in an accident, it does so over a period of 0.15 seconds.

a **Calculate** the magnitude of the:

i acceleration

ii impact force using Newton's second law formula $F = ma$

iii change in momentum

iv force using the relationship $Ft = \Delta p$.

b **Determine** whether the calculated force is the same for both methods (from parts **ii** and **iv**).

★ **16** **Clarify** what is wrong with defining momentum as the product of mass and speed.

★ **17** A rubber ball of mass 0.7 kg is dropped and strikes the floor with an initial velocity of 5 m s^{-1}. It bounces back with a final velocity of 3 m s^{-1}. **Determine** the change in the momentum of the rubber ball caused by the floor.

★ **18** A car of mass 2200 kg accelerates from rest at 3 m s^{-2} for 10 s. **Determine** the impulse imparted to the car.

★★ **19** A tennis ball of mass 58 g strikes a wall perpendicularly with a velocity of 10 m s^{-1}. It rebounds at a velocity of 8 m s^{-1}. **Determine** the change in the momentum of the tennis ball.

★★ **20** When a ball of mass 180 g is struck by a bat moving in the opposite direction, the force acting on the ball is as shown in the graph (Figure 3).

If the ball was initially moving at 10.1 m s^{-1} south, **determine** the:

a impulse

b final velocity of the ball.

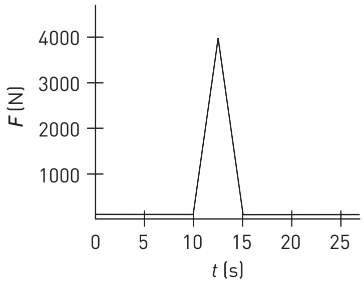

FIGURE 3 Graph of the force acting on the ball

★★ **21** An object of mass 5 kg moving with a velocity of 10 m s^{-1} strikes another of mass 3 kg at rest. The two masses continue in motion together. **Determine** their common velocity.

★★ **22** An archer fires an arrow of mass 96 g with a velocity of 120 m s^{-1} at a target of mass 1500 g hanging by a long piece of string from a tall tree. If the arrow becomes embedded in the target, **determine** the velocity with which the target moves.

FIGURE 4 An archer

★★ **23** Two masses of 4 kg and 3 kg respectively are travelling east along a frictionless surface with respective speeds of 12 m s^{-1} and 5 m s^{-1}. If the 3 kg mass continues to move east with a speed of 9 m s^{-1} after the collision, **determine** the speed of the 4 kg mass.

★★ **24** A rocket sled with a mass of 1500 kg is travelling at 100 m s^{-1} and at a certain time 200 kg of snow falls on it. **Determine** the final speed of the sled.

★★★ **25** Two motorcycles are involved in a head-on collision. Motorcycle A has a mass of 180 kg and was travelling at 110 km h^{-1} south. Motorcycle B has a mass of 200 kg and was travelling north at 90 km h^{-1}. Motorcycles A and B are about to collide.

a **Determine** the momentum of the system of the two bikes before the collision takes place.

The motorcycles collide and both riders are flung off and survive. However, the two bikes are a tangled mess that skids along the highway.

b **Calculate** the speed of the combined mass.

★★★ **26** The wearing of a seatbelt brings the vehicle occupant to rest over a distance of 30 cm and over a much longer time (both about 5 times greater than without a seatbelt). **Determine** the deceleration and force acting on a person's head (4 kg) if they were wearing a seatbelt. Set out your answer as in Table 1.

TABLE 1

Crash data	No seatbelt	Seatbelt
Impact speed (m s^{-1})	16.7	16.7
Distance before coming to rest (cm)	6	30
Deceleration (m s^{-2})	2324 (237 'g')	
Time to come to rest (ms)	7	
Change in momentum (kg m s^{-1})	66.8	66.8
Force (N)	9542	
Likelihood of skull fracture (low if < 2300 N)	High	

★★★ **27** A railway truck of mass 4000 kg moving with a speed of 3.6 m s^{-1} collides with a stationary truck of mass 2400 kg. The two trucks become coupled together. **Deduce** their common speed.

Investigate, evaluate and communicate

★ **28** **Propose** whether you could have a collision between two objects that have positive momentum and end up with them both having negative momentum.

★ **29** A newspaper said the evidence for seatbelts reducing deaths in car crashes is 'persuasive'. **Evaluate** this statement.

★★ **30** A game warden is trying to stop a charging pig and fires special 'safe' bean-bag pellets at it. The bags are 150 g each and travel at 30 m s^{-1}. If the pig has a mass of 40 kg and is running at 5 m s^{-1}, mathematically **solve** how many of these bean bags must strike the pig to stop it.

★★ **31** Can you jump off a chair onto the floor while holding a cup full of water without spilling any? **Devise** a plan for how you should land to do this.

★★★ **32** A bullet of mass 20 g travelling horizontally to the right at 700 m s^{-1} strikes a stationary wooden block of mass 2.0 kg resting on a smooth horizontal surface. The bullet goes through the block and comes out on the other side at 200 m s^{-1}. **Determine** the speed of the block after the bullet has come out the other side.

★★★ **33** A toy car of mass 1 kg moves left with a speed of 2 m s^{-1}. It collides head-on with a toy truck of mass of 1.5 kg moving with a speed of 1.5 m s^{-1} to the right. If the car rebounds at 2.05 m s^{-1}, **determine** the final velocity of the truck.

★★★ **34** A ball of mass 50 g moving horizontally at a speed of 40 cm s^{-1} strikes a suspended plate of mass 1000 g and rebounds from it with a speed of 25 cm s^{-1} as shown in Figure 5.

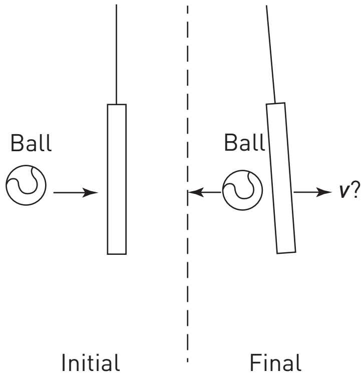

FIGURE 5 A ball strikes a suspended plate

Determine the speed with which the plate begins to move.

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CHAPTER 13

Work and energy

In simple terms, energy is the capacity to do work. The word ‘energy’ stems from the Greek *en* meaning ‘in’, and *ergos* meaning ‘work’. But this doesn’t give us a good understanding of the idea of energy and work. Physicists didn’t develop a good understanding of these concepts until 100 years after Newton’s death. Today, these ideas are considered fundamental to the processes of nature.

If you leave a torch turned on, its batteries will run out of energy. But has the energy gone forever? Where did it go? These are fundamental questions when it comes to energy. As you learnt earlier, energy is not lost – it just gets transferred from one place to another or transformed into another form of energy. This is called the law of conservation of energy. The universe seems to have a finite amount of energy that is continually being rearranged.

OBJECTIVES

→ Define the terms mechanical work, kinetic energy and gravitational potential energy.
→ Solve problems involving work done by a force.
→ Solve problems involving kinetic energy and gravitational potential energy.
→ Determine and interpret the area under a force–displacement graph.
→ Interpret meaning from an energy–time graph.
→ Define the terms elastic collision and inelastic collision.
→ Compare and contrast elastic and inelastic collisions.
→ Solve problems involving elastic collisions and inelastic collisions.

Source: *Physics 2019 v1.2 General Senior Syllabus Queensland Curriculum & Assessment Authority*

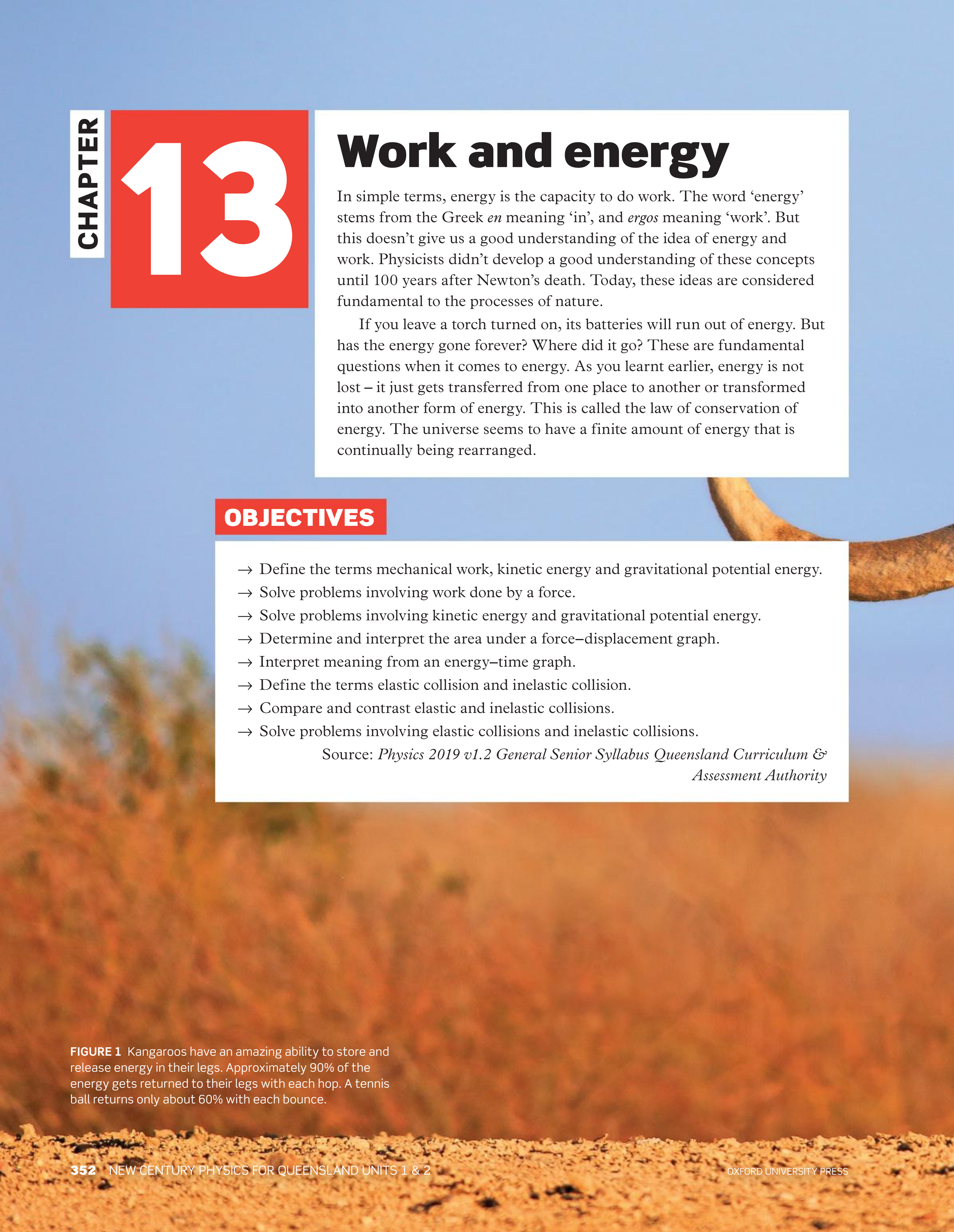

FIGURE 1 Kangaroos have an amazing ability to store and release energy in their legs. Approximately 90% of the energy gets returned to their legs with each hop. A tennis ball returns only about 60% with each bounce.

MAKES YOU WONDER

In this chapter we will be examining aspects of work and energy that will help to answer questions such as:

→ If you stand still you are using up energy, but where does the energy go?

→ When two cars collide where does all the kinetic energy go?

→ Will there really be an energy crisis soon? Are we running out of energy?

13.1 Forms of energy

KEY IDEAS

By the end of this unit, you will know about:

- types of mechanical energy
- energy losses and transfers.

kinetic energy
the energy due to the motion of an object, including the motion of particles in a substance (symbol: E_K; SI unit: joule; unit symbol: J)

gravitational potential energy
the energy stored in an object due to its position relative to another object to which it is attracted by the force of gravity (symbol: E_P; SI unit: joule; unit symbol: J)

mechanical energy
the sum of potential energy and kinetic energy of an object; the energy associated with its motion and position

Words such as light, thermal, electromagnetic, sound, mechanical, nuclear and chemical don't provide a systematic way of organising the different forms of energy. It is helpful to classify energy using the following categories:

- **Kinetic energy** – bodies that are moving have kinetic energy (E_K); for example, a flying bird, a shooting star, a moving locomotive, a roller coaster in motion, a speeding bullet, the wind and water.
- **Gravitational potential energy** – bodies that can do work because of their position have gravitational potential energy (E_P); for example, water in a reservoir, weights lifted off the ground and a roller coaster at the top of a rise.

Kinetic and gravitational potential energy are both forms of **mechanical energy**. Chemical, thermal, nuclear and electromagnetic energy are forms of internal energy (U). They are to do with the random vibrations or motions of electrons, protons, neutrons, atoms and molecules within an object. We will only deal with mechanical energy in this chapter.

Energy forms and transfers

Energy can be used to do work, such as when the water in a reservoir is used to turn a turbine (Figure 1). The reverse is also true – when work is done it can increase the energy of an object. For example, we can do work to pump water from a lake to a high reservoir. The stored water has higher energy because of its height, and can later be used to drive electric generators and produce electrical energy. When energy is transferred to an object, we say work is done **on** the object. When energy is transferred away from an object, we say that work is done **by** the object:

Work is done on the object when energy is transferred to an object.

Example: A speeding roller coaster rises up a slope and slows down.

This is $E_K \rightarrow E_P$.

Work is done **by** the object when energy is transferred **from** an object.

Example: A roller coaster runs down a slope and gains speed.

This is $E_P \rightarrow E_K$.

FIGURE 1 At the Wivenhoe Dam power station in Queensland, water is pumped from the lower reservoir (Wivenhoe Dam) up to the higher reservoir (Splityard Creek Dam), thus increasing the gravitational potential of the water.

Conservation of energy

You have heard many times that energy is conserved, and probably learnt it as the **law of conservation of energy** – that energy cannot be created or destroyed, just transformed from one form to another. Another way of saying the law is: the total energy of an isolated system remains constant (conserved) over time. By 'conserved', we mean staying the same.

law of conservation of energy
the total energy of an isolated system remains constant (conserved) over time

When work is done on an object, whether it be pumping water up to a dam, pushing a desk across a room or firing protons at a nucleus, the object gains energy. We can say energy is transferred to the object by the work being done. An equation called the work–energy equation states that the change in energy of the object is equal to the work done. This energy may be kinetic, potential or both combined.

Work–energy equation:

$$W = \Delta E$$

Alternatively, energy can be transferred from an object as the energy is used to do work. When a box slides down an incline at constant speed, the gravitational potential energy is being used to force the block along the surface. It is at constant speed, so the kinetic energy is not increasing. The change in gravitational potential energy does work on the box, hence $\Delta E = W$.

CHECK YOUR LEARNING 13.1

Describe and explain

1 **Explain** the types of energy that are considered to be mechanical energy.

2 **Describe** two differences between kinetic energy and gravitational potential energy.

Apply, analyse and interpret

3 A compressed spring has a lot of energy and can do work. **Deduce** whether its energy is in the form of potential or kinetic energy.

4 **Categorise** thermal energy as kinetic or potential energy.

Investigate, evaluate and communicate

5 When bodies interact, the energy of one may increase at the expense of another. However, we can't intercept the energy and bottle it. **Assess** the claim: 'Energy is not a thing; it is a property of a body.'

6 Per kilogram, humans produce 10 000 times the energy produced by the Sun. But which produces the greatest total heat – the Sun or all the people on Earth? **Determine** the energy output of the Sun by estimating the population of Earth, the average mass of a person, and knowing that the average heat output of a person is 12 megajoules per day.

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13.2 Work done by a force

KEY IDEAS

By the end of this unit, you will know about:

- what work is
- when work has occurred
- solving problems about work done by a force.

The best way to discuss energy is as a mathematical concept linked to work. Just talking about simple energy transfers and transformations is one way of presenting a difficult idea, but this makes energy seem like an invisible, intangible substance that can flow from place to place (which it is not).

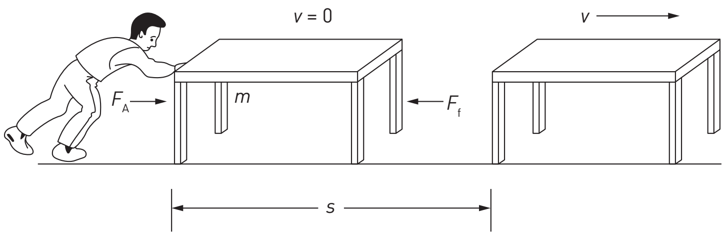

FIGURE 1 Doing work to shift a desk means applying a force over a certain distance.

Now for a little maths. Figure 1 shows a person trying to push a desk across the floor. The desk with mass *m* is moved from rest a distance *s* across the floor by an applied force $\boldsymbol{F}_A$ against the frictional force $\boldsymbol{F}_f$. It acquires a velocity $\boldsymbol{v}$. Remember that the symbols for vector quantities are shown in **bold**. Scalar quantity symbols are not.

work
the product of the force and the distance moved in the direction of an applied force

If you tried to push a desk across the floor and it didn't move, you might say you did a lot of work on the desk. But to a physicist, if it didn't move then no **work** was done. If you did move the desk, then the work done would depend on how hard you pushed and the distance the desk moved. Work is defined as the product of the force and the distance moved in the direction of an applied force. It is a scalar quantity, and yet is the product of two vector quantities. For instance, if you applied a horizontal force $\boldsymbol{F}$ and shifted the desk through a horizontal displacement $\boldsymbol{s}$, work done is the product of the force and the distance moved in the direction of the applied force.

$$\text{Work} = \text{force} \times \text{displacement}$$

$$W = \boldsymbol{F}\boldsymbol{s}$$

WORKED EXAMPLE 13.2

Calculate the work done when a constant horizontal force of 3 N is used to push a book a distance of 2 m along a desk (Figure 2).

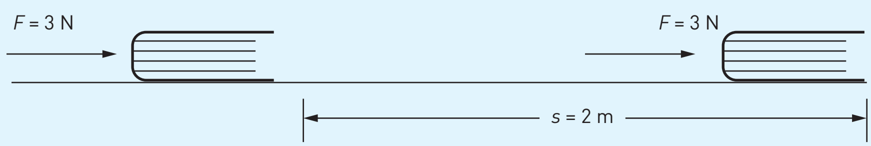

FIGURE 2 Work done on the book by applying a force

SOLUTION

$W = \boldsymbol{F}\boldsymbol{s} = 3 \times 2 = 6$ J

Force and displacement are both vector quantities, so their symbols are shown in bold. However, work is not a vector quantity.

Doing no work in class

According to our definition of work, you are not doing any work on a book (in a scientific sense) if you hold it in your outstretched arm for a long period of time. Although you get tired, no work is done on the book. You will feel tired because your muscles are using energy and burning up fuel. As the muscle fibres relax and contract keeping your arm still, you are using energy – but this energy is not being transferred to the book. Because of this, no work has been done on the book. However, there is a change in the internal energy of your body as internal motions and reactions occur.

The same is true for a helicopter hovering in a stationary position above the ground. These motions never result in any measurable displacement and therefore never do any work (in the way 'work' is used in the physics sense).

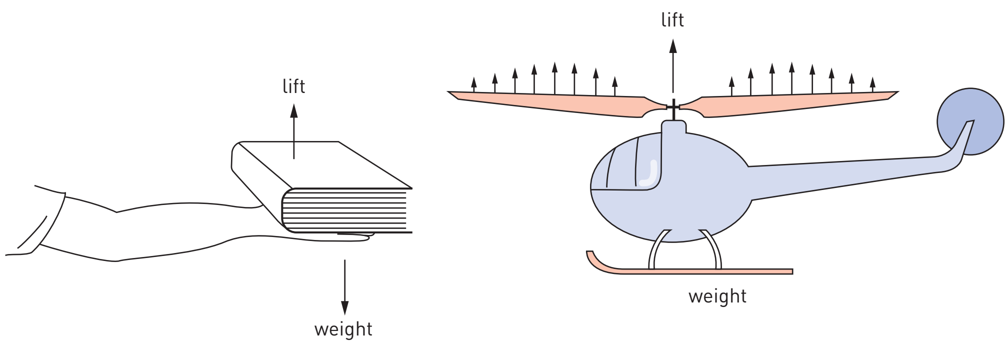

FIGURE 3 No work is done on the book or the helicopter if there is no movement.

Force–displacement graphs

We can depict the work done when a force moves an object by use of force–displacement graphs. The simplest case is for a constant force – for example, pushing a desk across a room. A more complicated case is when the force is variable – such as pushing the desk over tiles, and then carpet and so on.

Constant and variable forces

In Figure 4(a), a constant horizontal force of 150 N is applied to an object and shifts it a horizontal distance of 100 m. The work done is simply the product of $\boldsymbol{F} \times \boldsymbol{s}$, which is the shaded area under the line of a force–displacement graph (15 000 J). If the force does not remain constant but varies, as in Figure 4(b), the work is still determined by calculating the shaded area (13 000 J).

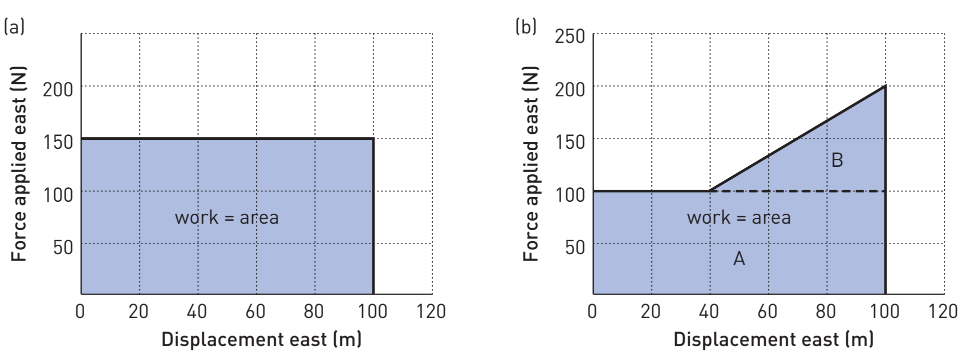

FIGURE 4 Work done is the area under a force–displacement graph. (a) Area = 150 × 100 = 15 000 J; (b) Area = area of rectangle A + area of triangle B = (100 × 100) + $\frac{1}{2}$(60 × 100) = 13 000 J.

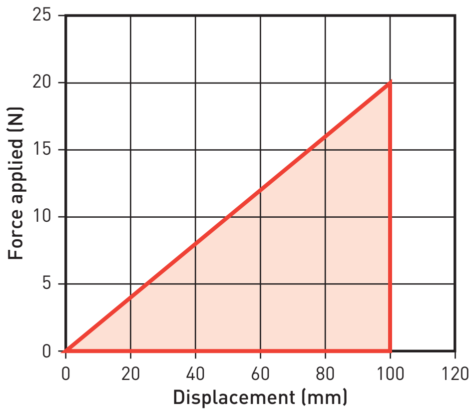

FIGURE 5 The change in length of a spring (horizontal axis) as masses are added to it. Work done is the area under the graph line (the shaded triangle).

FIGURE 6 A Mars Bar gives you 1 235 000 J of energy.

Uniformly varying force – a spring

The graphs in Figure 4 show both constant and a varying force, but there are circumstances where the force varies in a uniform manner, such as with stretching a spring or bending a plastic ruler. Figure 5 shows the change in length of a spring (in mm, horizontal axis) as masses are added to it (in N, vertical axis).

The work done is the product of force times displacement, which is the area under the line. In this case, the work done is calculated as:

$$\begin{aligned} W &= \boldsymbol{Fs} \\ &= \frac{1}{2}(\text{base} \times \text{height}) \\ &= \frac{1}{2}\left(\frac{100}{1000} \times 20\right) \text{ (convert mm to m)} \\ &= 1.0 \text{ J} \end{aligned}$$

Lifting an object

When calculating the work done in lifting an object vertically, the force applied will be equal to the object's weight ($\boldsymbol{F}_W = m\boldsymbol{g}$). This is assuming it is lifted at constant speed. If the speed is varied, then Newton's second law formula ($\boldsymbol{F} = m\boldsymbol{a}$) would be applied.

We can use these formulas to calculate the work done in lifting an object, such as lifting a 15 kg schoolbag at constant speed from the floor to a port rack 1.2 m off the ground.

$$\boldsymbol{F}_W = m\boldsymbol{g} = 15 \times 9.8 = 147 \text{ N (weight of the bag)}$$

$$W = \boldsymbol{Fs} = 147 \times 1.2 = 176 \text{ J}$$

A Mars Bar provides you with 1 235 000 J of energy. This is equivalent to lifting your bag 7000 times to burn off the energy. It seems hardly worth the effort! Luckily your body uses up a lot more energy in lifting a bag than just the amount needed to overcome gravitational forces.

CHECK YOUR LEARNING 13.2

Describe and explain

1 **Explain** the relationship between the area under a force–displacement graph and the work done.

2 **Explain** if you are doing any work when you push hard against a rock, but it doesn't move.

3 **Calculate** the amount of work done in the following:
   - a pulling a bag of dog food 3.5 m along a table by applying a 25 N horizontal force
   - b lifting a 20 kg bag of dog food at constant speed on to a table 85 cm off the ground
   - c pumping 200 kg of water at a constant flow rate into a tank 25 m high.

4 A team of two horses is pulling a loaded cart in a northerly direction along a horizontal road at constant speed. The force–displacement graph is shown in Figure 7.

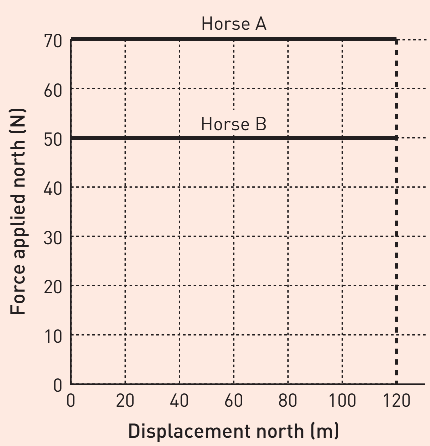

FIGURE 7 Force–displacement graph

   - a **Calculate** the work done by each horse.
   - b **Calculate** the total work done on the cart.

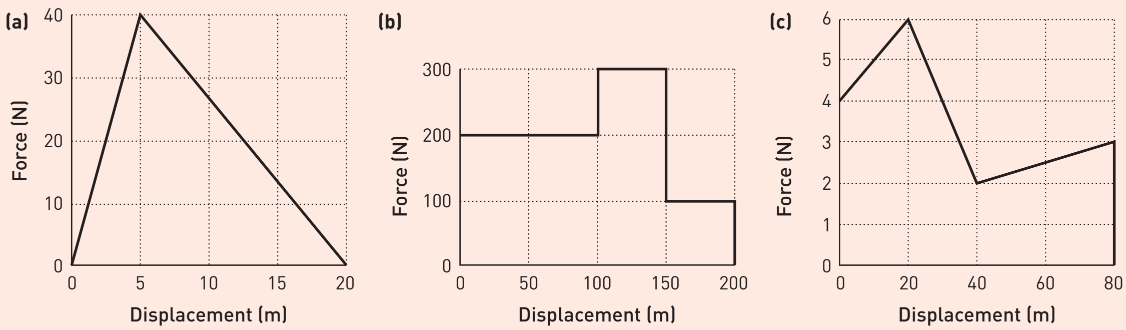

FIGURE 8 Graphs of different forces acting on different objects

5 Figure 8 shows different forces acting on different objects. **Calculate** the work done in each case.

6 **Construct** a force–displacement graph of a schoolbag of mass 10 kg being raised vertically at constant speed to a height of 2.0 m.

Investigate, evaluate and communicate

7 A 200 kg piano is lowered by a rope out of a third-floor window.

- a **Calculate** how much work is done in lowering the piano a distance of 9 m to the ground at constant speed.
- b **Decide** whether work was done on or by the piano in this process.

8 The graph in Figure 9 shows how an object has accelerated as it travels along a road a distance s. Note that it is an acceleration–displacement graph.

- a If the mass of the object is 4 kg, **determine** how much work is done by the 50 m mark.
- b **Construct** a force–displacement graph of the motion.

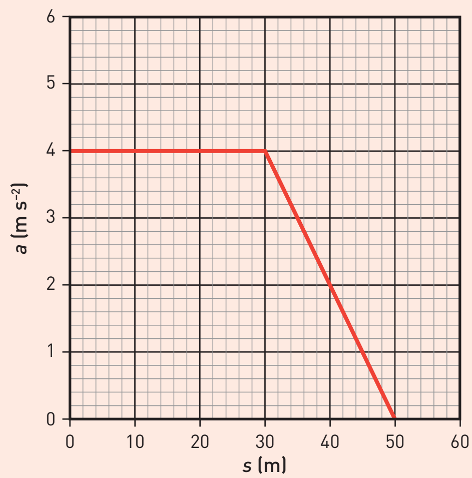

FIGURE 9 Acceleration–displacement graph

9 **Comment** on the assertion that the area under a force-displacement graph is a measure of the change of energy of an object.

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13.3 Solving problems: E_K and E_P

KEY IDEAS

In this section, you will learn about:

- solving problems involving kinetic energy and gravitational potential energy
- how mechanical energy is conserved
- applications of energy transfers
- energy–time graphs.

FIGURE 1 A moving bowling ball contains a lot of kinetic energy that gets transferred during a collision.

Kinetic energy

A bowling ball resting on the floor has no energy of motion, but when it rolls along the floor it is said to have energy of motion. Energy due to the motion of an object is called kinetic energy (Greek *kinema* = 'motion').

Equation for kinetic energy

To determine an equation for kinetic energy, we will use concepts already developed. Imagine a hockey puck moving on a frictionless surface such as an air table.

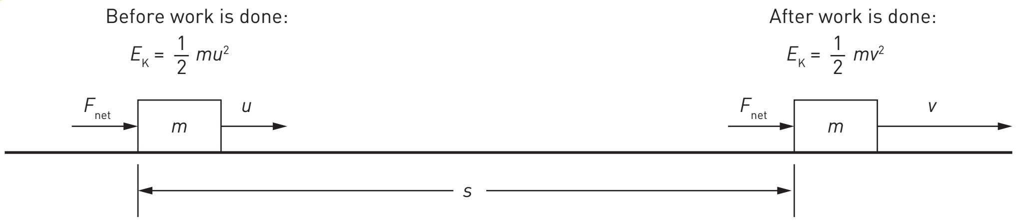


FIGURE 2 Motion of a hockey puck on an air table

If an unbalanced force F_{net} is applied to it for a period of time t, the force produces accelerated motion and the object goes from an initial velocity u to a final velocity v. This can be expressed as:

$$v^2 = u^2 + 2as$$
$$a = \frac{v^2 - u^2}{2s}$$

By letting $F = ma$, the work done in accelerating the puck is given by:

$$\begin{aligned} W &= Fs \\ &= mas \\ &= m\left(\frac{v^2 - u^2}{2s}\right) \times s \\ &= \frac{1}{2}mv^2 - \frac{1}{2}mu^2 \end{aligned}$$

This represents a change in the quantity we call kinetic energy.

Work done equals change in kinetic energy:

$$W = \Delta E_K$$

Hence, if an object starts from rest, its final kinetic energy is given by:

$$E_K = \frac{1}{2}mv^2$$

Study tip

Kinetic energy (E_K) is a scalar quantity and does not require direction.

WORKED EXAMPLE 13.3A

Calculate the kinetic energy of a 6.0 kg bowling ball sliding at 5.0 m s^{-1}.

SOLUTION

$E_K = \frac{1}{2}mv^2 = \frac{1}{2} \times 6 \times 5^2 = 75$ J

WORKED EXAMPLE 13.3B

A 520 kg rocket sled at rest is propelled along the ice by an engine developing a constant thrust of 12 000 N over a distance of 40 m. Assuming all of the work goes into motion, calculate

a the work done by the engine on the sled after 40 m

b its velocity after 40 m (using the kinetic energy formula).

SOLUTION

Work done by engine:

a $W = Fs = 480\,000$ J

b Work is converted to kinetic energy, hence $E_K = 480\,000$ J

$$E_K = \frac{1}{2}mv^2$$

$$480\,000 = \frac{1}{2} \times 520\ v^2$$

$$v = \sqrt{\frac{2 \times 480\,000}{520}} = 43\ \text{m s}^{-1}$$

Gravitational potential energy

When you lift something off the floor and put it on a desk, you are applying a force to the object and displacing it – you are doing work on it. If work is done, then it gains energy. Actually, it is not so much the object that gains energy – it is the system made up of the object and Earth that gains energy.

When you lift something, you increase the separation distance between the object and Earth. It is this system, this gravitational field, that gains energy. We look at gravitational fields in more detail in Unit 3. For now, it is simpler to say the object itself has gained energy.

If the object is lifted at constant speed, it is not gaining kinetic energy but instead gaining energy of position. This is called gravitational potential energy (Latin *potens* = 'capable', meaning capable of doing work). Gravitational potential energy has the symbol E_P.

FIGURE 3 Lifting weights off the ground increases their gravitational potential energy. The weightlifter applies a force to separate Earth and the weights from each other.

The work done is a measure of the change in gravitational potential energy. If the object is lifted at constant speed, then the force applied equals its weight (F_W) and the vertical distance (height, Δh) through which it is moved:

$$\Delta E_p = mg\Delta h$$

For example, a 5 kg ball raised 20 m (Δh) will have work done on it or a change in potential energy equivalent to $5 \times 9.8 \times 20$ J = 980 J. We assume that an object on the ground has zero E_P, so the E_P of the ball is 980 J. We say that objects raised off the ground gain E_P and objects falling lose E_P.

WORKED EXAMPLE 13.3C

Calculate the E_p of a 20 kg box of groceries lifted 0.75 m to a bench top.

SOLUTION

$\Delta E_p = mg\Delta h$

$= 20 \times 9.8 \times 0.75$

$= 147$ J

Note that it is actually the system of the box and Earth that has increased its E_p by 147 J, but we don't usually take this into consideration.

WORKED EXAMPLE 13.3D

A 35 kg barrel is rolled up a 5 m long plank, which makes a 30° angle to the ground. What is the E_p of the barrel at the top (Figure 4)?

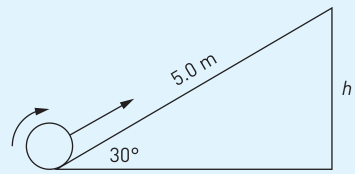


FIGURE 4 Barrel being rolled up an incline

SOLUTION

A 30° incline with a hypotenuse of 5 m has a vertical height given by: 5.0 sin 30° = 2.5 m.

$\Delta E_p = mg\Delta h$

$= 35 \times 9.8 \times 2.5 = 860$ J

Note that it doesn't matter how the barrel was raised the 2.5 m. It could have been rolled up an incline 10 m long and the E_p would be the same.

Mathematically, $\Delta E_p = mg\Delta h$. This will only be true over distances where the gravitational force remains constant. When you get too far away from Earth's surface, this relationship does not hold as g becomes less than 9.8 m s^{-2}.

Conservation of mechanical energy

Mechanical energy was earlier described as including both kinetic and potential energy. The total mechanical energy of a system can be defined as the sum of kinetic and potential energy. Within an isolated system, this mechanical energy is conserved.

When a ball is thrown upward in the air, it starts with a high kinetic energy and then at the top of its travel when it stops moving it has none. The kinetic energy has been transferred into the gravitational potential energy of the ball (and Earth).

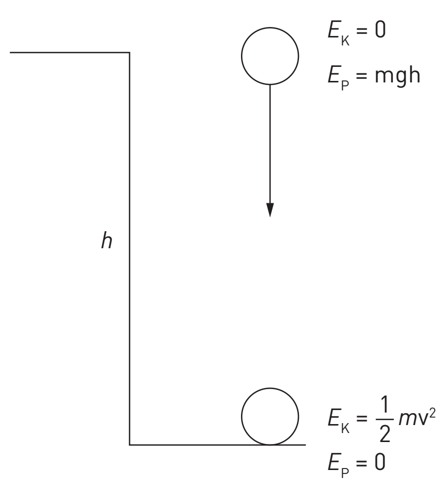


FIGURE 5 A ball loses E_p and gains E_K as it falls.

Table 1 shows how the E_P and E_K change as the ball falls. Note that the total energy is constant at 1000 J.

TABLE 1 E_P and E_K of the ball at different heights as it falls

Height (m)	Potential energy *mgh* (J)	Kinetic energy $\frac{1}{2}mv^2$ (J)	Total $E_P + E_K$ (J)	Velocity (m s^{-1})
100	1000	0	1000	0
75	750	250	1000	22
50	500	500	1000	32
25	250	750	1000	39
0	0	1000	1000	45

Applications of energy transfers

The ability of mechanical energy to be converted into useful work has been known for thousands of years. Some examples of transfers are presented here.

Amusement parks

Amusement parks are the perfect place to find examples of physics principles. If you were to visit Queensland's Dreamworld, you would witness Newton's laws, the conservation of momentum, centripetal forces, rotation and weightlessness.

FIGURE 6 A roller coaster ride. The carriages have a large amount of gravitational potential energy that is about to be transformed into kinetic energy.

Energy changes during a roller coaster ride

The roller coaster is a good example of conservation of mechanical energy (Figure 7). At the start, electrical energy is used to drag the carriages to a great height (point A), giving them high gravitational potential energy. At the point of release, the kinetic energy is almost zero. As the carriages roll down the tracks, E_P is converted to E_K and the carriages accelerate (point B). At the next hill, some of the E_K is converted back to E_P, but some is transferred to thermal energy (by friction) and sound and the carriages can never rise (point D), but never as high as at the start.

If there was no energy transfer to the structure, then mechanical energy would be conserved and the sum of E_P and E_K would be constant. However, there is always some loss and the roller coaster designers take this into account. The energy losses become quite small on rainy days because frictional losses are reduced and high speeds result. Sometimes the speeds are too high and roller coasters have to be closed.

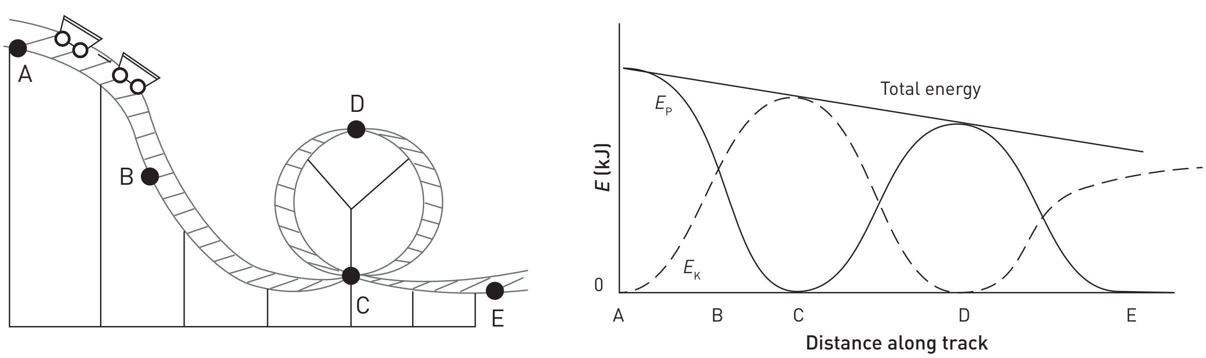


FIGURE 7 Roller coaster ride and an energy graph

CHALLENGE 13.3

Roller coasters

A roller coaster is made up of carriages A, B and C. The three carriages enter a loop as shown in Figure 8. Out of positions 1, 2, 3 and 4, which position will give the greatest speed for:

a carriage A?

b carriage B?

c carriage C?

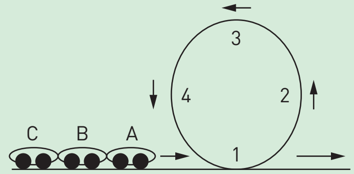


FIGURE 8 Four stages around a roller coaster loop

Study tip

An example of conservation of energy on Dreamworld's Tower of Terror ride can be found on your obook assess.

Energy–time graphs

It is useful to be able to interpret meaning from energy–time graphs. The graphs in Figures 9 and 10 show the changes in kinetic and gravitational potential energy with time as a ball is dropped from 1 m high onto a hard, flat, horizontal surface.

elastic potential energy
potential energy stored as a result of deformation of an elastic object, such as the stretching of a spring

Figure 9 is a theoretical energy–time graph for a ball of 100 g (0.100 kg) raised to 1.0 m high. It has 0.98 J of E_P and zero E_K. As it falls, the E_P drops and the E_K rises by an equal amount. After striking the surface where both E_K and E_P are both zero (the energy has been transferred to elastic potential energy), the ball rebounds and the E_K starts off with a high value then decreases. The graph in Figure 10 is a real-world version of the theoretical graph.

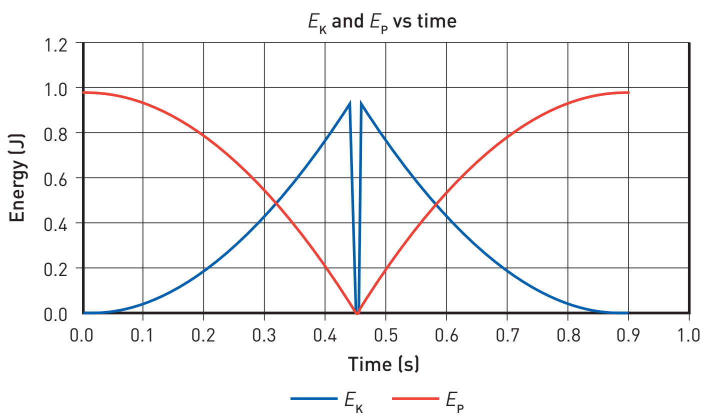


FIGURE 9 Theoretical energy–time graph for a ball bouncing off a horizontal surface

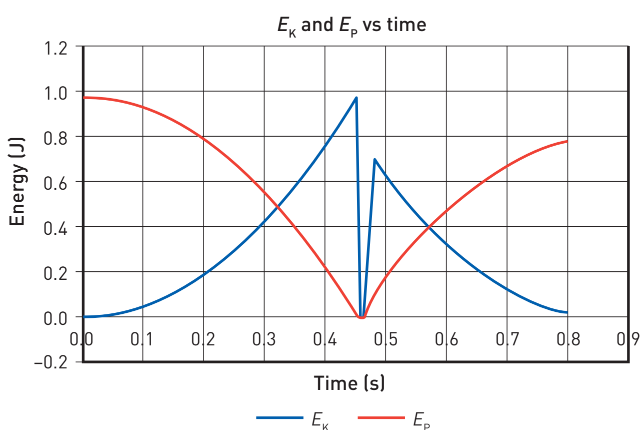


FIGURE 10 'Real-world' energy–time graph for a ball bouncing off a horizontal surface. Note that some energy is 'lost' (probably transformed to heat) in the collision.

FIGURE 11 A weightlifter performing a clean and jerk

CHECK YOUR LEARNING 13.3

Describe and explain

1 A ball dropped from a height of 100 cm bounces back to a height of 60 cm.
   a **Calculate** the percentage of its original E_p that is in the ball at the 60 cm mark.
   b **Explain** where the rest of the energy went.

2 Use conservation of mechanical energy principles to **calculate** the impact speed of a 65 kg diver who dives off a platform 8.5 m above the water.

Apply, analyse and interpret

3 Champion weightlifter Leonid Taranenko lifted 266 kg in a clean and jerk to a height of 2.4 m.
   a **Calculate** how much work he did lifting this.
   b **Calculate** the impact speed when he dropped the weight onto the mat from this height.

4 A stroller can be pushed up a ramp 10 m long to get to a height of 1.0 m. **Consider** why doing the same work to push a stroller up a 5 m ramp to get to the same height of 1.0 m is so much harder.

Investigate, evaluate and communicate

5 For the graph in Figure 9:
   a **Determine** for how long the ball was stationary.
   b **Calculate** how much energy was converted to elastic potential energy during the stationary period.

   For the ball in Figure 10:
   c **Describe** its motion and explain how you interpreted this from the graph.
   d **Discuss** how momentum is conserved in this collision (Hint: think of the desk).

6 When a ball bounces off the floor, it has no E_p or E_K at its moment of impact. **Propose** where the energy has gone.

Check your obook assess for these additional resources and more:

» **Student book questions**
Check your learning 13.3

» **Challenge**
13.3 Roller coasters

» **Increase your knowledge**
Conservation of energy at Dreamworld's Tower of Terror

» **Weblink**
Roller coasters

13.4 Energy changes and collisions

KEY IDEAS

In this section, you will learn about:

+ elastic and inelastic collisions
+ solving 'explosions' problems.

In chapter 12 we saw that, in all collisions, momentum is conserved. We will now look at conservation of kinetic energy in collisions. Collisions can be either elastic or inelastic. The word elastic comes from the Greek *elastikós* meaning 'to drive' or 'propel'.

Elastic collisions

elastic collision a collision in which kinetic energy is conserved

Collisions where energy is conserved are referred to as **elastic collisions**. The word 'conserve' is from the Latin for 'to preserve' or 'keep the same'. Jams are often called conserves because they preserve the fruit. In elastic collisions, the total amount of kinetic energy before the collision is the same as the total kinetic energy after the collision. Collisions between gas molecules are perfectly elastic. If they weren't, the gas would lose energy and the pressure in a spray can would decrease while it was sitting on a shelf. Clearly this does not happen.

$$E_K(\text{before}) = E_K(\text{after})$$

$$\Sigma\frac{1}{2}mv^2_{\text{before}} = \Sigma\frac{1}{2}mv^2_{\text{after}}$$

FIGURE 1 Newton's cradle

A collision between steel ball bearings is also approximately elastic. Consider the case of colliding balls in the device known as Newton's cradle (Figure 1).

The ball on the left has kinetic energy as it approaches the stationary balls. It collides, and the energy is passed along the balls as one ball collides with the next. At the right, the end ball rises to the same height as the first ball was released from. Because it rises to the same height, we say the collision was elastic and no energy was lost. Obviously some energy would be lost as the heights get less and less as time goes by, but it is almost perfectly elastic.

Let's consider the law of conservation of mechanical energy in the collision of two steel balls.

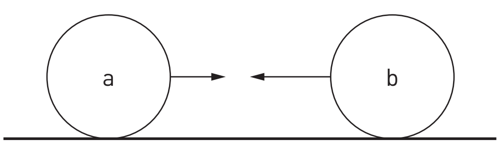


FIGURE 2 Two rigid balls colliding head-on is an elastic collision

Assuming it is an elastic collision:

$$E_K(\text{before}) = E_K(\text{after})$$

$$\Sigma\frac{1}{2}mv^2_{\text{before}} = \Sigma\frac{1}{2}mv^2_{\text{after}}$$

$$\frac{1}{2}mu_a^{\ 2} + \frac{1}{2}mu_b^{\ 2} = \frac{1}{2}mv_a^{\ 2} + \frac{1}{2}mv_b^{\ 2}$$

Solving elastic collision problems

Sometimes we are given the details of a collision and need to apply this relationship – for example, to see if it is an elastic collision or not. To determine this, we need to see if the kinetic energy is conserved in the collision. If it is conserved, then it is elastic.

Summary

For an elastic collision:

$$\text{kinetic energy is conserved: } \Sigma\frac{1}{2}mv^2_{\text{before}} = \Sigma\frac{1}{2}mv^2_{\text{after}}$$

$$\text{momentum is conserved: } \Sigma mv_{\text{before}} = \Sigma mv_{\text{after}}$$

WORKED EXAMPLE 13.4A

A 3 kg steel ball moving east at 4 m s^{-1} collides with a stationary 1 kg ball. After the collision, the 3 kg mass moves east at 2 m s^{-1} and the 1 kg mass moves east at 6 m s^{-1} (Figure 3). Is this collision elastic?

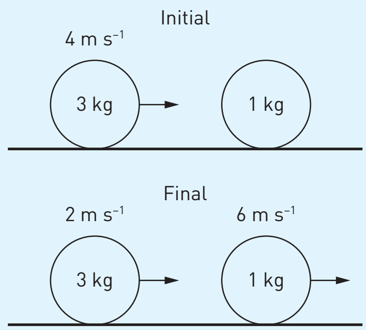


FIGURE 3 Is this collision elastic?

SOLUTION

We can use the previous formula for elastic collisions to determine the kinetic energy before and after the collision, and see if kinetic energy is conserved.

$$E_K(\text{before}) = \frac{1}{2}mu_a{}^2 + \frac{1}{2}mu_b{}^2$$
$$= \frac{1}{2} \times 3 \times 4^2 + \frac{1}{2} \times 1 \times 0^2$$
$$= 24 \text{ J}$$
$$E_K(\text{after}) = \frac{1}{2}mv_a{}^2 + \frac{1}{2}mv_b{}^2$$
$$= \frac{1}{2} \times 3 \times 2^2 + \frac{1}{2} \times 1 \times 6^2$$
$$= 24 \text{ J}$$

The final kinetic energy is the same as the initial, therefore the collision is elastic. Note: check for yourself that momentum is conserved.

Solving problems using conservation of energy and momentum

With some collision problems you need to use conservation of momentum and conservation of kinetic energy to achieve a solution.

WORKED EXAMPLE 13.4B

Object A of mass 1.0 kg moving at 3.0 m s^{-1} to the right collides elastically head-on with object B of mass 1.0 kg moving at 2 m s^{-1} to the left. Determine the final velocity of each object.

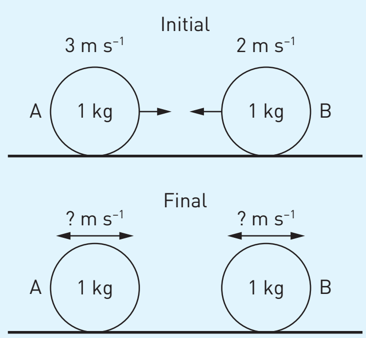


FIGURE 4 What is the final velocity of each object after the collision?

SOLUTION

Determining the final velocity of each object requires a number of steps involving some complex thinking.

Conservation of momentum:

$$p_{before} = p_{after}$$
$$\Sigma m v_{before} = \Sigma m v_{after}$$
$$m_A u_A + m_B u_B = m_A v_A + m_B v_B$$
$$1 \times 3 + 1 \times -2 = 1 \times v_A + 1 \times v_B$$
$$3 - 2 = v_A + v_B$$
$$1 = v_A + v_B$$
$$v_A = 1 - v_B$$

Conservation of kinetic energy:

$$E_K(\text{before}) = E_K(\text{after})$$
$$\Sigma \frac{1}{2} m v^2_{before} = \Sigma \frac{1}{2} m v^2_{after}$$
$$\frac{1}{2} m u_A{}^2 + \frac{1}{2} m u_B{}^2 = \frac{1}{2} m v_A{}^2 + \frac{1}{2} m v_B{}^2$$
$$\frac{1}{2} \times 1 \times 3^2 + \frac{1}{2} \times 1 \times -2^2 = \frac{1}{2} \times 1 \times v_A{}^2 + \frac{1}{2} \times 1 \times v_B{}^2$$

Multiply both sides by 2 to cancel out the $\frac{1}{2}$.

$$9 + 4 = v_A{}^2 + v_B{}^2$$
$$13 = v_A{}^2 + v_B{}^2$$
$$v_A{}^2 = 13 - v_B{}^2$$

Solving both equations simultaneously and eliminating the term v_A, hence:

$$v_A{}^2 = (1 - v_B)^2 = 1 - 2v_B + v_B{}^2 \text{ and } v_A{}^2 = 13 - v_B{}^2$$
$$1 - 2v_B{}^2 + v_B{}^2 = 13 - v_B{}^2$$
$$2v_B{}^2 - 2v_B - 12 = 0$$

Using the quadratic formula or factorising into $(v_B - 3)(v_B + 2) = 0$ gives two solutions for v_B. They are $v_B = 3$ m s^{-1} and –2 m s^{-1}. The second of these solutions is the case where the velocities are the same as the initial. In other words, no collision took place – they were on parallel but separate tracks. The first solution is where a collision took place. In this case, $\boldsymbol{v}_B = 3$ m s^{-1} and substituting this into the equation $\boldsymbol{v}_A = 1 - \boldsymbol{v}_B$ gives a value for $\boldsymbol{v}_A$ of –2 m s^{-1} (2m s^{-1} to the left).

FIGURE 5 When a billiard ball has an elastic collision with another ball of equal size, they swap velocities. This is sometimes called the pool player's result.

Worked example 13.4B is a long procedure and students find many pitfalls. If you are careful and meticulous, and practise many more examples, success should be yours.

Equal masses colliding elastically

In Worked example 13.4B where objects A and B collided head-on, the objects swapped their velocities. Objects A and B had initial speeds of 3 m s^{-1} and –2 m s^{-1} respectively, but after collision these had become –2 m s^{-1} and 3 m s^{-1} respectively. This is true of linear elastic collisions between objects of equal mass. It is sometimes called the pool player's result (Figure 5).

Energy–time graphs

Another useful type of graph is the energy–time graph. The graph in Figure 6 shows the changes in E_K when a moving trolley collides elastically with a stationary one of the same mass. Notice that the line remains at 1.0 J for the first 2.5 seconds as the moving trolley approaches the stationary trolley. When they meet (at 2.6 s), the spring between them is compressed and the E_K reduces as the trolley slows. At maximum compression of the spring, the E_K is zero as it has all been transferred to the spring as potential energy. Then the second trolley takes off as the spring expands and transfers its potential energy to the trolley and its E_K increases. The E_K of the first trolley remains at zero as it stays in place. Because it is an elastic collision, the total E_K at the end of the collision is the same as at the beginning.

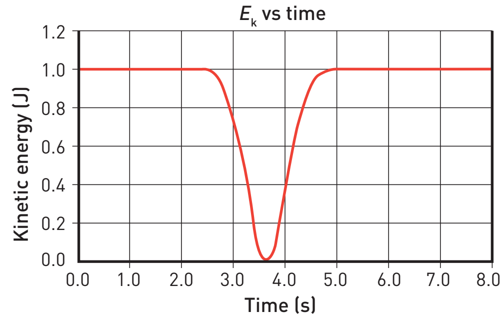


FIGURE 6 Energy–time graph for an elastic collision

Inelastic collisions

In an **inelastic collision**, kinetic energy is said to be 'lost'. It is not really lost – the missing kinetic energy is transferred to other types of energy such as thermal (heat) energy and sound. Most collisions in the real world are inelastic collisions. When two objects cling or lock together after impact (become coupled), the collision is inelastic. An inelastic collision is one in which the total kinetic energy is **not** conserved.

inelastic collision a collision in which total kinetic energy is not conserved

Examples include:

- cars colliding
- bullet hitting a target
- meteorite striking Earth
- tennis ball being struck by a racquet.

Summary

For an inelastic collision:

Kinetic energy is **not** conserved: $\Sigma\frac{1}{2}mv^2_{before} \neq \Sigma\frac{1}{2}mv^2_{after}$

Momentum is (always) conserved: $\Sigma mv_{before} = \Sigma mv_{after}$

When different objects are dropped onto a concrete floor, they bounce to different heights. A perfectly elastic collision would see the ball returning to its original height. A superball is about 90% elastic, a golf ball about 60% and a lump of putty is perfectly inelastic.

Although there is always some bounce associated with collisions, in this section we will deal with collisions that are almost totally inelastic for the sake of simplicity.

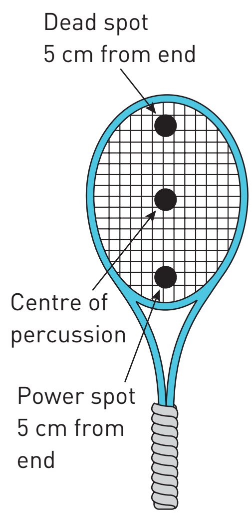


FIGURE 7 Tennis balls undergo inelastic collisions with a tennis racquet. Different spots on the racquet provide different levels of bounce (kinetic energy changes).

WORKED EXAMPLE 13.4C

A body of mass 6 kg travelling east at 4 m s^{-1} strikes a 2 kg mass at rest. After the collision they remain coupled and the mass moves east at 3 m s^{-1}. Is the collision elastic or inelastic?

SOLUTION

$$E_K(\text{initial}) = \frac{1}{2}mu_A{}^2 + \frac{1}{2}mu_B{}^2$$
$$= \frac{1}{2} \times 6 \times 4^2 + \frac{1}{2} \times 2 \times 0^2$$
$$= 48 \text{ J}$$
$$E_K(\text{final}) = +\frac{1}{2}mv_A{}^2 + 8$$
$$= \frac{1}{2}(6 + 2) \times 3^2$$
$$= 36 \text{ J}$$

As kinetic energy is lost, the collision is not elastic.

Explosions

explosion
a single object rapidly separating into two or more fragments

An **explosion** can be thought of as a single object rapidly separating into two or more fragments. Some familiar explosions were given in the previous chapter:

- a firecracker blowing into fragments
- an alpha particle ejected out of a nucleus
- blood pumping out of your heart.

The motion of an exploding object can be determined using conservation of momentum principles. This is because momentum is conserved for all interactions, regardless of whether they are explosions or collisions. On the other hand, kinetic energy is only conserved for elastic interactions – an explosion is definitely not an example of this.

For example, in the previous chapter we considered a 10 kg object at rest that exploded into two fragments: a 4 kg piece (m_1) travels west at 15 m s^{-1} (v_1), and a 6 kg piece (m_2) moved east at an unknown speed. We could calculate this speed using conservation of momentum:

$$\Sigma p_{\text{before}} = \Sigma p_{\text{after}}$$
$$(m_1 + m_2)u = m_1v_1 + m_2v_2$$
$$10 \times 0 = 4 \times 15 + 6 \times v_2$$
$$v_2 = -10 \text{ m s}^{-1} \text{(the negative sign means east)}$$

However, consider the kinetic energy before and after the explosion:

Before: $\Sigma\frac{1}{2}mv^2_{\text{before}} = \frac{1}{2}(m_1 + m_2)u^2 = \frac{1}{2}(10) \times 0^2 = 0 \text{ J}$

After: $\Sigma\frac{1}{2}mv^2_{\text{after}} = \frac{1}{2}m_1v^2 + \frac{1}{2}m_1v^2 = \frac{1}{2} \times 4 \times 15^2 + \frac{1}{2} \times 6 \times (-10)^2 = 450 + 300 = 750 \text{ J}$

0 J ≠ 750 J, therefore kinetic energy is not conserved.

Relationships such as this can be applied to all sorts of explosions. However, only the conservation of momentum law can be applied to the motion of objects before and after an explosion. Once you know the mass and velocity of the exploded fragments, you can then work out their kinetic energy.

Study tip

Energy	Momentum
Energy is not conserved in an explosion, so you cannot use conservation of kinetic energy principles to solve explosion questions.	Momentum is conserved in explosions, so you should use conservation of momentum principles.
$\Sigma\frac{1}{2}mv^2_{\text{before}} \neq \Sigma\frac{1}{2}mv^2_{\text{after}}$	$\Sigma mv_{\text{before}} = \Sigma mv_{\text{after}}$

CHECK YOUR LEARNING 13.4

Describe and explain

1 **Describe** the difference between an elastic and an inelastic collision in terms of conservation of momentum and of kinetic energy.

2 **Recall** whether colliding steel balls are considered to have elastic or inelastic collisions.

3 **Explain** what it means to say gas molecules have elastic collisions. Describe what would happen if they didn't.

4 Two objects of equal mass collide head-on in an elastic collision.
   a **Describe** what happens to their velocities.
   b **Explain** why this situation is sometimes called the pool player's result.

5 a **Construct** a graph showing the total kinetic energy on the vertical axis and the time of the horizontal axis for a pool ball undergoing an elastic collision with another pool ball initially at rest.
   b **Construct** a similar graph for a pool ball undergoing an inelastic collision with another pool ball initially at rest.

6 A brick of mass 2.5 kg is lifted to a height of 2.5 m above the ground by a bricklayer. **Calculate** the:
   a E_p acquired by the brick
   b work done by the bricklayer in lifting it.

Apply, analyse and interpret

7 The graph in Figure 8 (also presented earlier in this topic) shows the changes in E_K when a moving trolley collides elastically with a stationary one of the same mass. Answer the questions in relation to this graph.
   a **Sketch** the graph and add to it the elastic potential energy as time goes by.
   b **Construct** a line showing the total energy ($E_K + E_P$) of the trolley with time.
   c **Determine** how this graph would change if the mass of the incoming trolley was twice the existing mass.
   d **Sketch** and explain how the graph would change if, instead of the collision being elastic, the original two trolleys became coupled.

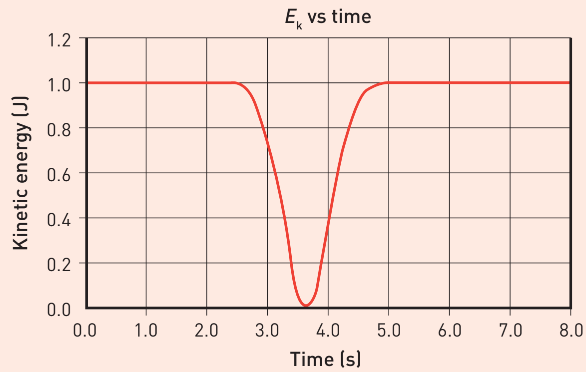


FIGURE 8 Energy–time graph for an elastic collision

8 **Consider** a collision between two lawn bowls, each of mass 300 g. Ball 2 is at rest and ball 1 is moving towards it with a speed of 2 m s^{-1}. After the balls collide elastically, ball 1 comes to an immediate stop and ball 2 moves off.
   a **Calculate** the speed of ball 2 using conservation of kinetic energy principles given that the collision is elastic.
   b **Determine**, using calculation, that momentum is also conserved (as it always is).

9 Imagine a game of marbles. A girl rolls a blue marble of mass 100 g along the ground at a speed of 3 m s^{-1}, to the right towards the red marble (mass 50 g) initially at rest. After the marbles collide elastically, the blue marble is moving at 1 m s^{-1} to the right. **Determine** the final speed of the red marble.

10 Ball A of mass 0.20 kg, moving with a speed of 1.75 m s^{-1} approaches a stationary ball B of mass 0.15 kg, and collides head-on. After the collision, ball B travels at 2.0 m s^{-1} in the same direction.
   a **Calculate** the speed of ball A after the collision.
   b **Determine** if the collision was elastic.

Check your obook assess for these additional resources and more:

» Student book questions
Check your learning 13.4

» Video
Newton's Cradle

» Video
Energy collisions

» Video worksheet
Newton's cradle
Energy collisions

CHAPTER 13

Review

Summary

13.1
- Energy is not lost in any transfer – it just gets transferred from one place to another or from one form to another. This is called the law of conservation of energy.
- Energy is the capacity to do work.

13.2
- Work is defined as the product of the force and the distance moved in the direction of the applied force, $W = Fs$. Work has the unit newton metre or Nm. The newton metre is called the joule (J).
- Work done is the area under a force–displacement graph.

13.3
- Bodies that are moving have kinetic energy (E_K): $E_K = \frac{1}{2}mv^2$.
- Work done equals change in energy: $W = \Delta E$.
- Bodies that can do work because of their position have gravitational potential energy (E_p): $\Delta E_p = mg\Delta h$
- Gravitational potential energy is defined as the energy associated with the state of separation between bodies that attract each other via the gravitational force.
- Kinetic and potential energy are said to be forms of mechanical energy.
- Within an isolated system, mechanical energy is conserved. $E_K + E_p$ = constant.

13.4
- There are two types of collisions: elastic and inelastic.
- In an elastic collision, total kinetic energy is conserved.
- In an inelastic collision, the total kinetic energy is not conserved.
- In both elastic and inelastic collisions, momentum is conserved.
- In an explosion, only momentum is conserved, not kinetic energy.

Key terms

- elastic collision
- elastic potential energy
- explosion
- gravitational potential energy
- inelastic collision
- kinetic energy
- law of conservation of energy
- mechanical energy
- work

Key formulas

Work	$W = \Delta E$
Work	$W = Fs$
Kinetic energy	$E_K = \frac{1}{2}mv^2$
Change in gravitational potential energy	$\Delta E_p = mg\Delta h$
Elastic collision	$\Sigma\left(\frac{1}{2}\right)mv^2_{before} = \Sigma\left(\frac{1}{2}\right)mv^2_{after}$

Revision questions

The relative difficulty of these questions is indicated by the number of stars beside each question number: ★ = low; ★★ = medium; ★★★ = high.

Multiple-choice

1 A lift (elevator) is operated by an electric motor. It moves between the 10th floor and the 2nd floor at constant speed. One main energy transformation during this journey is:

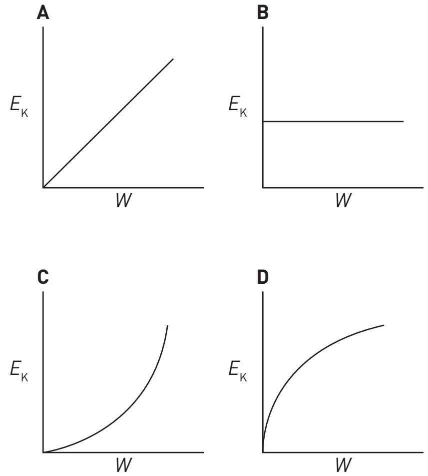
A gravitational potential energy → kinetic energy.

B electrical energy → kinetic energy.

C kinetic energy → thermal energy.

D electrical energy → thermal energy.

2 A constant force acts on a mass that is initially at rest. Which of the following graphs best shows how the kinetic energy E_K of the mass changes with the work W done on the mass? Friction is negligible.



3 Which of the following is a correct definition of work?

A Product of force and distance

B Product of force and distance moved in the direction of the force

C Product of power and time

D Product of force and displacement

4 A pump extracts water from a well of depth h at a constant rate of R kg s^{-1}. What is the power required to raise the water?

A $\frac{R}{gh}$

B Rgh

C $\frac{Rg}{h}$

D $\frac{hg}{R}$

5 A truck driver slams on the brakes of a truck moving with a velocity v. As a result of his action the truck stops after travelling a distance d. If the driver had been travelling with twice the velocity, what would be the stopping distance compared to the distance in the first trial?

A Two times greater

B Four times greater

C Half as much

D One-quarter as much

Short answer

Describe and explain

★ 6 **Define** kinetic energy, gravitational potential energy, elastic potential energy, law of conservation of energy, work, mechanical work and power.

★ 7 **Calculate** the gravitational potential energy of a 50 kg bag of cement lifted 1.4 m from the ground to a mixer bowl.

★ 8 **Calculate** the kinetic energy of a 120 kg object that is moving with a speed of 15 m s^{-1}.

★ 9 **Calculate** the kinetic energy of a 60 g air-hockey puck sliding at 8.0 m s^{-1}.

★ 10 An arrow of mass 75 g is fired directly upwards at a speed of 60 m s^{-1}.

a **Calculate** the E_P at its highest point.

b **Calculate** how high this highest point is.

★★★ 11 A glass ball (ball A) of mass 100 g is rolled to the right along the ground at 3 m s^{-1} toward a stationary ball (ball B) of mass 50 g. After they collide elastically, both balls are moving. **Calculate** the final velocity of each ball.

★★★ 12 Car A of mass 1500 kg is moving at a speed of 10 m s^{-1} to the left and collides inelastically with car B at rest. Car B has a mass of 1200 kg.

a **Calculate** the velocity of the resulting mass.

b If the combined mass rolled 2.6 m before coming to a halt, **calculate** the force that must have been acting to stop it moving.

Apply, analyse and interpret

★ **13** A car is pulling a loaded trailer in an easterly direction along a horizontal road at constant speed. A force–displacement graph is shown in Figure 2. **Determine** the work done by the car.

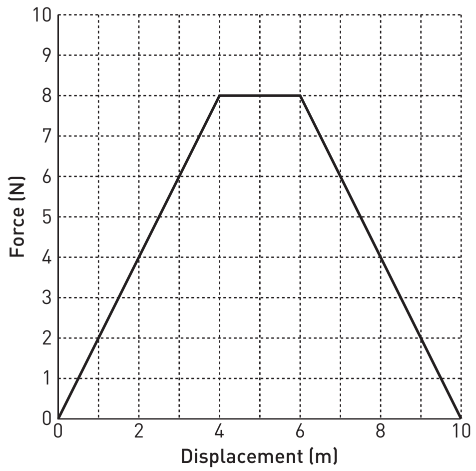


FIGURE 2 Force–displacement graph

★ **14** A body of mass 10 kg travelling east at 4 m s^{-1} strikes a 3 kg mass at rest. After the collision, the bodies remain coupled and the mass moves east at 3 m s^{-1}. **Deduce** whether the collision is elastic or inelastic.

★ **15** An object has a kinetic energy of 250 J and a mass of 17 kg. **Determine** how fast the object is moving.

★ **16** It takes a horizontal force of 75 N to pull a 20 kg box across the floor at constant speed.

- **a** **Calculate** how much work is done in shifting the box 3.0 m.
- **b** If there was no friction, **determine** what acceleration this box would experience.

★ **17** **Distinguish** between an elastic collision and an inelastic collision.

★ **18** A basketball with a mass of 2.2 kg falls off a 50 m high window ledge. **Determine** its gravitational energy after 2 seconds have elapsed.

★ **19** On Earth, a ball of mass 0.70 kg is kicked straight up. **Determine** its gravitational potential energy at its highest point, 6.5 m off the ground.

★ **20** **Determine** the impact speed of a 2 kg rock dropped off a cliff 8.5 m above the water (using conservation of mechanical energy principles).

★★ **21** A student is asked to carry a 15 kg carton of books from the ground floor to the first floor. **Deduce** which way uses the least energy: to walk up the stairs slowly or to run up.

★★★ **22** A 1.6 kg ball collides with a 2.4 kg ball. After the collision, the balls continue to travel, as shown in Figure 3.

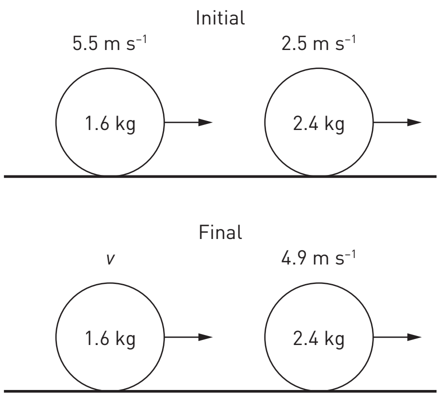


FIGURE 3 Diagram of a collision involving two balls of different mass

- **a** **Calculate** the velocity *v*.
- **b** **Determine** whether the collision is elastic or inelastic. **Explain** your reasoning.
- **c** If the velocity of the 2.4 kg ball was in the opposite direction initially, **determine** the velocity of the 1.6 kg ball after the collision in the direction shown in the Figure 3. (Warning, this will take you an hour or more).

★★★ **23** Two inflatable boats (X and Y) are at rest in a swimming pool and are 1.5 m apart. A boy of mass 60 kg jumps from boat X into boat Y at a speed of 1.0 m s^{-1}. The boats move away from each other. Given that mass of boat X = 50 kg, mass of boat Y = 40 kg and mass of boy = 60 kg, **determine**:

- **a** the velocity of boat X after the boy jumps.
- **b** the velocity of boat Y just after he lands in it.

Given that friction between the boats and the water is 3.0 N, **calculate**:

- **c** how far apart the boats will be when they come to rest.

★★★ **24** A 0.63 kg ball is thrown straight up into the air with an initial speed of 14 m s^{-1} and reaches a maximum height of 8.1 m before falling back down again. Assuming that the only forces acting on the ball are the ball's weight and air drag, **deduce** the work done on the ball during the ascent by the air drag.

★★★ **25** A body of mass 2.0 kg makes an elastic collision with another body at rest and continues to move in the same direction but with one-fourth of its original speed (Figure 4). **Determine** the mass of the struck body.

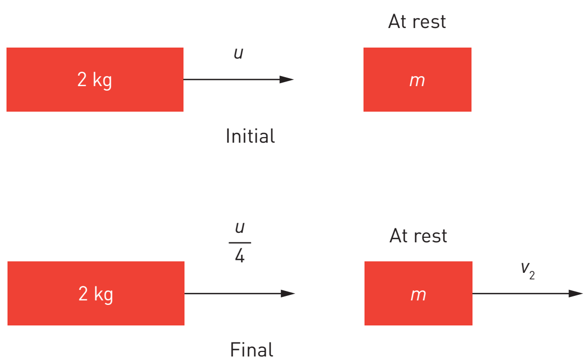


FIGURE 4 Diagram of an elastic collision

★★★ **26** A London Underground train consisting of a locomotive and 30 carriages with a total mass of 1586 tonnes travelling at 28 km h^{-1} is slowed by travelling up a slight incline to the horizontal platform. If the train is raised vertically by 1.2 m over a distance of 300 m, **determine** the speed of the train at the top of the incline (assuming no braking takes place).

Investigate, evaluate and communicate

★★★ **27** The baseball manufacturer Rawlings said they hadn't changed the manufacturing process of balls since 1931. However, it seems odd that balls from the 1970s bounced 157 cm when dropped from 462 cm (15 foot), whereas balls from the 1990s bounced 208 cm. Also intriguing is that, in the 1970s, players hit 61 home runs per season, whereas in the 1990s they hit 68 home runs. **Propose** why this change occured.

★★★ **28** Pigs don't fly – if they could, they would have about 150 kJ of E_p flying at a height of 100 m. **Predict** the mass of a flying pig.

★★★ **29** A motor consumes 60 J of electrical energy per second but only converts this to 18 J of mechanical energy per second.
Propose where the remaining 42 J goes.

★★★ **30** When two lumps of clay hit each other head-on, they form a big lump. **Decide** where the kinetic energy went.

★★★ **31** Two billiard balls, each with a mass of 150 g, collide head-on in an elastic collision. Ball 1 was travelling right at a speed of 2 m s^{-1} and ball 2 at a speed of 1.5 m s^{-1}. After the collision, ball 1 travels in the reverse direction at a velocity of 1.5 m s^{-1}.

a **Calculate** the velocity of ball 2.

b **Justify** the conclusion that the collision was elastic.

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CHAPTER 14

Waves

Waves carry energy, and this energy can be related to movement up or down as well as forward. Consider the energy carried by a tsunami – a giant wave produced in the ocean after a volcano or earthquake. Tsunamis often cause more destruction and damage than the event that created them. Areas that are affected frequently by tsunamis, including Japan and Hawaii, go to great efforts to detect the source of earthquakes by measuring wave velocities. This allows governments to estimate the time of a tsunami's arrival so that people can be warned and can evacuated.

Because of the energy waves carry, the motion of ocean waves has become one of the latest sources for generating electricity.

OBJECTIVES

→ Recall that waves transfer energy.
→ Define the term mechanical wave.
→ Compare the terms transverse wave and longitudinal wave.
→ Describe examples of transverse and longitudinal waves, such as sound, seismic waves and vibrations of stringed instruments.
→ Recall the terms compression, rarefaction, crest, trough, displacement, amplitude, period, frequency, wavelength and velocity, identifying them on graphical and visual representations of a wave.
→ Interpret and calculate the amplitude, period, frequency and wavelength from graphs of transverse and longitudinal waves.
→ Solve problems involving the wavelength, frequency, period and velocity of a wave.
→ Define the terms reflection, refraction, diffraction and superposition.
→ Using the wave model of light, explain phenomena related to reflection and refraction.
→ Describe the reflection and refraction of a wave at a boundary between two media.
→ Apply the principle of superposition to determine the resultant amplitude of two simple waves.
→ Explain constructive interference and destructive interference of two simple waves.
→ Explain the formation of standing waves in terms of superposition with reference to constructive and destructive interference, and nodes and antinodes.

Source: *Physics 2019 v1.2 General Senior Syllabus Queensland Curriculum & Assessment Authority*

MAKES YOU WONDER

In this chapter you will learn about concepts of wave energy and how to answer questions such as:

→ If you catch a wave in towards the beach, what exactly is moving in towards the beach?
→ When you hit a baseball, it speeds off with lots of kinetic energy. Where is the energy stored?
→ Why was it so hard to detect gravity waves if gravity is all around us?
→ When sunlight travels to Earth, is the energy carried through space like a moving ball or an ocean wave?
→ How do waves carry energy?

PRACTICALS

SUGGESTED PRACTICAL	**14.1** Longitudinal and transverse waves on springs

FIGURE 1 Waves rolling in with crests are about 15 surfboard-lengths apart, so that gives a wavelength of about 30 m. The time between crests was 12 seconds, so that's a speed of 2.5 m s^{-1}.

14.1 Mechanical model of waves

KEY IDEAS

In this section, you will learn about:

- mechanical waves
- amplitude
- transverse and longitudinal waves.

medium
an elastic substance such as air or water that allows for the transfer of energy in the form of a mechanical wave

mechanical waves
waves that require an elastic medium for the transfer of energy

electromagnetic waves
waves that require no medium for transmission and travel at the speed of light in a vacuum; includes long wavelength radio waves through to short wavelength gamma rays (called the electromagnetic spectrum)

amplitude
the distance of a point, in a wave, from the rest position (equilibrium position) to the crest position, which is half the vertical distance from a trough to a crest

displacement
the distance between a particle's position and the equilibrium position

equilibrium
the natural or resting position assumed by a medium if no disturbance was travelling through it

Waves are classified according to how they transfer energy. If a **medium** (a substance such as air or water) is required for the transfer of energy, then the waves are called **mechanical waves**. If no medium is required and the waves can travel through a vacuum, then the waves are called **electromagnetic waves**. This chapter and the next (Sound) will only discuss mechanical waves.

FIGURE 1 A circular wave is formed when a rock (or water droplets in this case) are dropped into water.

Picture a still pool of water. When a stone is dropped in, a circular wave is seen to radiate outward from the point where the stone enters the water. In this case, the water is the medium for the wave.

Amplitude

To create a wave, you must create a disturbance in an undisturbed (still) medium. The wave will continue to go outward until it runs out of energy. How is this loss of energy seen? The height of the wave is called the **amplitude** of the wave (Latin *amplus* = 'large, abundant'). It is the maximum **displacement** of a point on the wave from rest in the **equilibrium** position. Amplitude is shown as A in Figure 2.

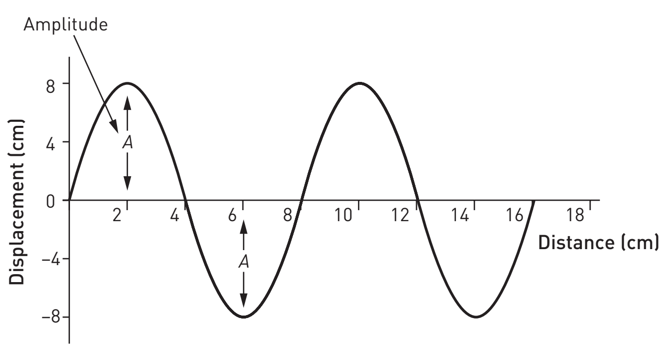

FIGURE 2 The amplitude of a wave is the maximum displacement of a point on the wave from the equilibrium position.

If there were no waves in the ocean on one particular day, the water would be in its equilibrium position. The word equilibrium comes from the Latin meaning 'equal balance' – the crests and troughs are balanced out and appear flat. The wave height is the bottom of the trough to the top of a crest.

The amplitude of a large water wave might be 10 m. This suggests the wave would have large amounts of energy. The larger the amplitude, the more energy the wave possesses. The energy of the wave comes from the **disturbance**. When a stone is thrown into a pond, some of the kinetic energy of the stone is transferred to the water wave. As you go further from the source of the wave, the amplitude of the wave becomes less as the energy **dissipates,** which means that the energy gets transformed to other forms, such as heat and sound.

When a surfer is in the ocean, they will move up and down as a wave passes but they will return to their original position once the wave has passed. The position of rest that the surfer is in is the equilibrium position (Figure 3).

When children hold the ends of a skipping rope and flick it, a wave (or pulse) moves from the flicked end to the other. This energy can be felt by a child at the other end of the rope. The energy and the pulse move along the skipping rope without the particles that make up the rope moving towards the receiver. The direction of energy flow is called the **direction of propagation**.

disturbance
a displacement from the equilibrium position of a vibrating system

dissipate
to lose energy (and hence, for a wave, amplitude) over time

direction of propagation
the direction of energy flow for a wave

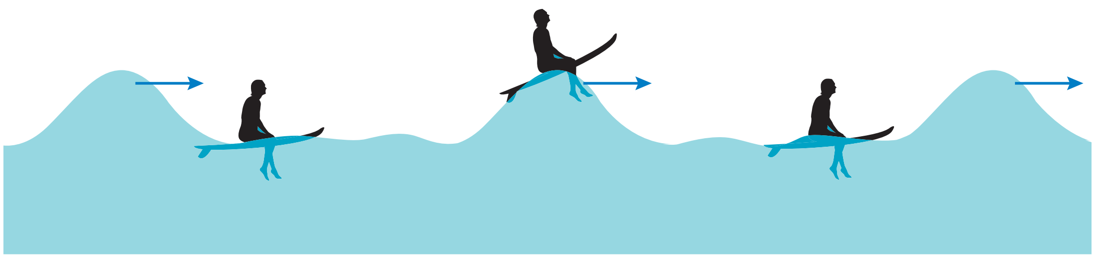

FIGURE 3 A surfboard rider moves up and down as a wave passes.

Transverse waves

Water waves and rope waves are a particular type of wave. As seen in Figure 3, the water (and the surfer) move upward as the wave passes. The particles that make up the water move at right angles to the direction the wave is travelling. This is the same for the rope wave. The rope moves upward as the pulse passes and then goes back to its original position (Figure 4).

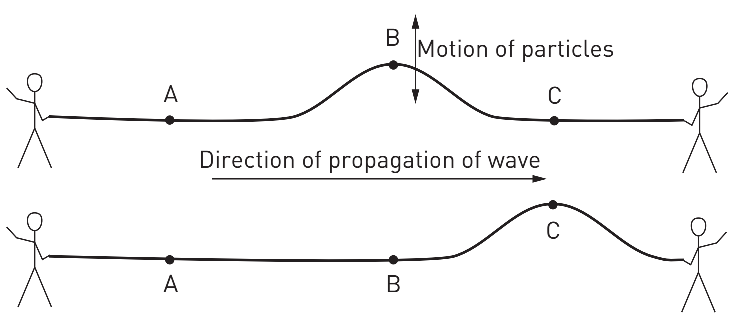

FIGURE 4 The parts of a rope move up and down as waves pass.

FIGURE 5 Radio waves are also an example of transverse waves.

transverse waves waves where the direction of oscillation of particles is perpendicular to the direction of energy transfer

Waves that move in this manner are called **transverse waves**. Transverse comes from the Latin *transvertere* meaning 'to turn across'. Each point of the wave vibrates perpendicularly to the direction the wave is travelling – perpendicular to the direction of propagation of the wave.

Examples of transverse waves include waves in water, ropes, hoses and springs. Waves of electromagnetic radiation (light, radio waves, and television waves) are also transverse.

Notice the direction of the motion of the particles of a spring as a transverse wave passes (Figure 6).

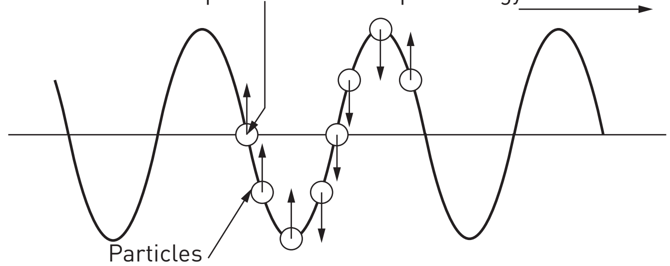

FIGURE 6 In a transverse wave, the particles move at right angles to the motion of the wave. The direction of individual particles is given by the arrows.

Longitudinal waves

longitudinal waves waves where the direction of oscillation of particles is parallel to the direction of energy transfer or wave movement

Another type of wave is a compression or **longitudinal wave**. Examples of these can be created in springs by compressing a part of a spring and then letting it go so the compression travels down the spring.

The following diagrams show the difference between transverse waves (Figure 7(a)) and longitudinal waves (Figure 7(b)).

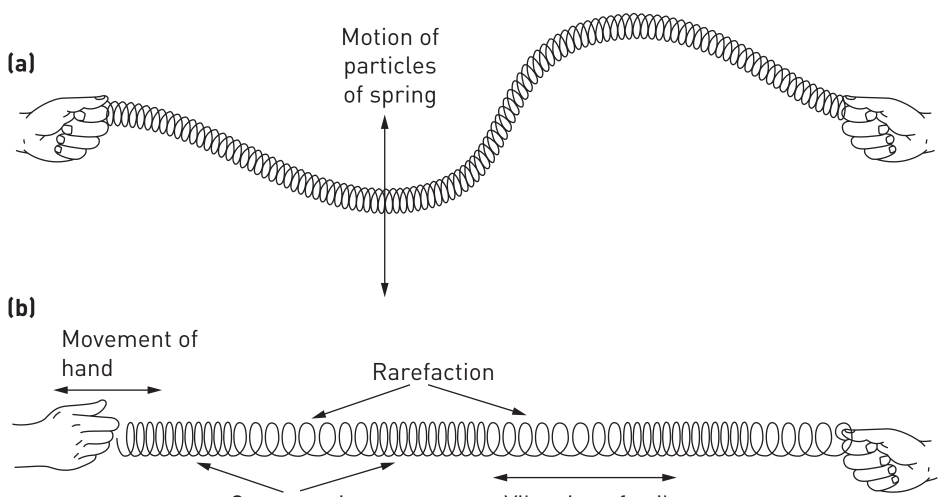

FIGURE 7 (a) Transverse waves; (b) Longitudinal waves

SUGGESTED PRACTICAL

14.1 Longitudinal and transverse waves on springs
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The particles of a spring propagating longitudinal waves vibrate in the same direction as the pulse is moving. This creates **compressions** and **rarefactions**.

The main characteristics of the two wave types are summarised in Table 1.

compression
a region in a longitudinal wave where the particles are closest together

rarefaction
a region in a longitudinal wave where the particles are furthest apart

TABLE 1 Summary of main characteristics of different wave types

	Mechanical	Electromagnetic
Is a medium needed for propagation?	yes	no
Transverse example	water, springs, strings	light
Longitudinal example	Slinky, sound	–

CHECK YOUR LEARNING 14.1

Describe and explain

1 **Explain** what is meant by amplitude.
2 **Describe** the process of equilibrium.
3 **Define** the term 'mechanical wave' and distinguish from the other type.
4 Use an example to **describe** two differences between a longitudinal wave and a transverse wave.
5 **Recall** the name of a medium that can support a transverse mechanical wave.
6 For the wave in Figure 8, **calculate** the value (in cm) of:
   a the wave height
   b the amplitude
   c the wavelength.

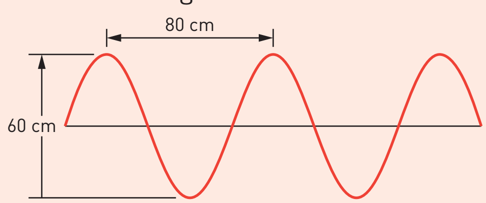

FIGURE 8 Waveform

Apply, analyse and interpret

7 **Clarify** the difference between compression and rarefaction.
8 If the energy in a longitudinal wave travels from south to north, **determine** the direction that the particles of the medium would be vibrating.

Investigate, evaluate and communicate

9 **Devise** a method to demonstrate experimentally that energy is carried by a wave.
10 **Evaluate** this statement: 'Waves transmit energy and momentum.'

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» Suggested practical
14.1 Longitudinal and transverse waves on springs

» Video
Wave motion

» Weblink
Waves

14.2 Characteristics of waves

KEY IDEAS

In this section, you will learn about:

- wavelength, crests, troughs and phase
- frequency of a wave
- period of a wave
- the wave equation
- velocity of a wave
- graphical and visual representations of a wave.

pulse
single disturbance produced in a medium by a source

wavelength
the minimum distance between two points on the wave in phase

phase
the position of a point in time on a waveform cycle; particles in phase have the same motion (velocity and amplitude) at a moment in time

crest
the highest part or point of a wave, or the points of maximum positive displacement

trough
the lowest part or point of a wave, or the points of maximum negative displacement

A single disturbance produced in a medium by a source, such as a flicking rope, is called a **pulse** (Latin *pulsus* = 'beating'). If a continuous set of pulses is produced by a source with a constant time interval between the generation of each pulse, the result is a wave.

Wavelength, crests, troughs and phase

The **wavelength** is the minimum distance between two points on the wave that are in **phase**. This can be explained as the distance between corresponding points on successive waves. The phase is the fraction of the wave cycle that has elapsed relative to the origin.

For example, the wavelength is the distance between two consecutive **crests** or two successive **troughs**. If the two points are in phase, they are at the same distance from the rest position and are moving in the same direction at the same time.

In Figure 1, D and H are in phase as they are on the equilibrium position and about to move up. C and E are out of phase as C is about to move down whereas E is about to move up. The wavelength, for example, is between G and K, O and Q, or B and F.

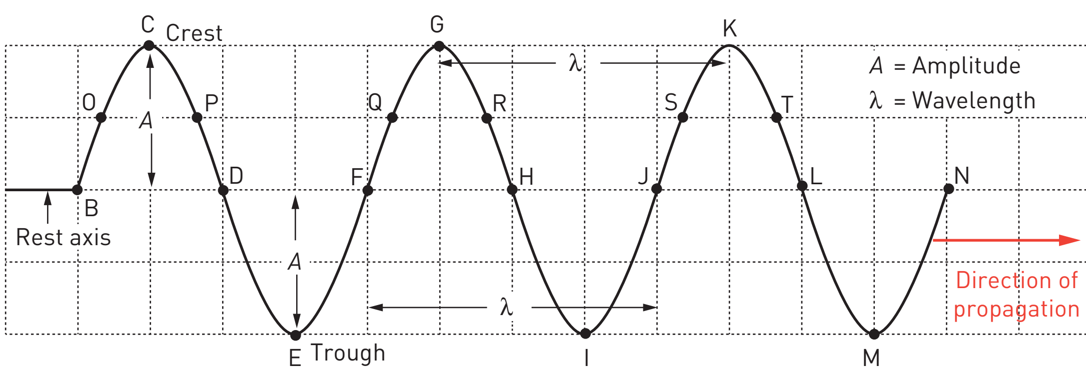


FIGURE 1 Wave characteristics of typical transverse waves

It is a little harder to see and measure the wavelength of a longitudinal wave. It is the distance between the middle of adjacent compressions or adjacent rarefactions, as shown in Figure 3(c). The symbol λ is the Greek 'L' (lambda) and is used for length.

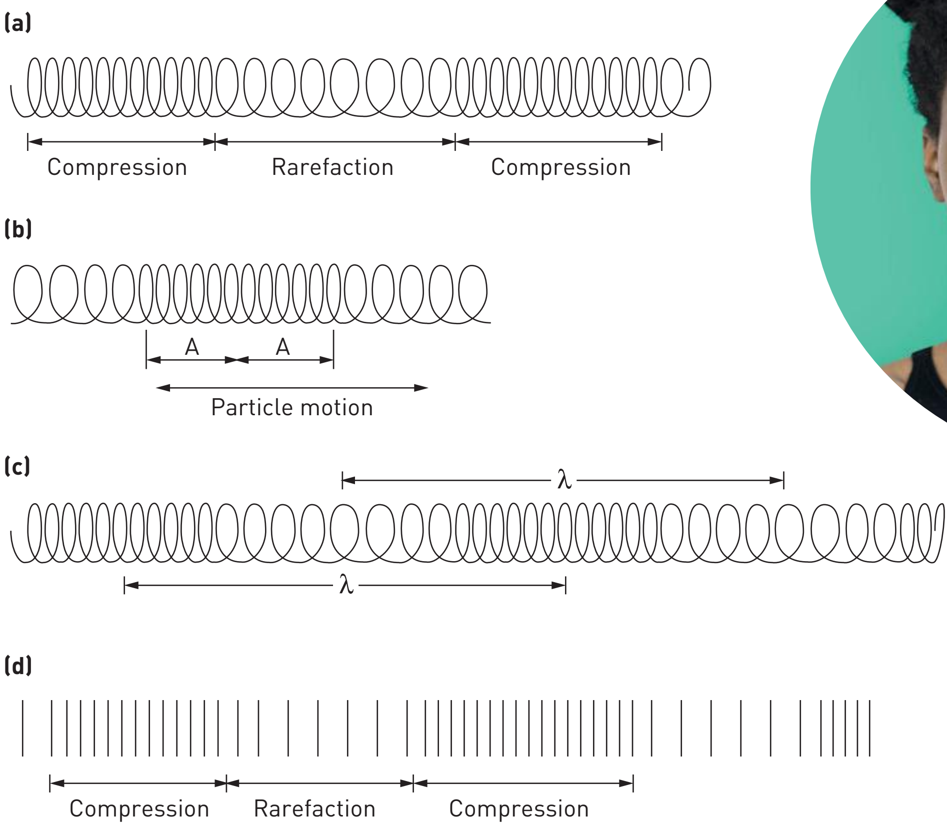


FIGURE 3 Wave characteristics of typical longitudinal waves

FIGURE 2 If the average rate of jaw movement is 100 Hz what does this really mean?

Frequency

The **frequency** *f* of a wave is the number of waves passing a given point per second or the number of waves created by the source per second. The unit for frequency is waves per second, or cycles per second (cps or s^{-1}), or the modern unit of a hertz (Hz). This is named after German physicist Heinrich Hertz (1857–1894) who discovered a technique for transmitting and receiving radio waves in the 1880s. A hertz is one cycle per second.

For example, if four crests pass a point in 1 s, then the frequency is 4 Hz. If the time between ocean waves was 10 s, the frequency would be $\frac{1}{10}$ or 0.1 Hz. The frequency of visible light waves is between 4×10^{14} Hz and 8×10^{14} Hz. The range of frequencies of sound waves that humans can hear is 20–20 000 Hz.

frequency
the number of oscillations of a wave source per second; measured in hertz (Hz)

CHALLENGE 14.2

Bubblegum

An issue of the prestigious *New England Journal of Medicine* reported that the average rate of jaw movement of gum chewers in the United States is 100 Hz. What do you suppose they really meant?

Period

The **period** of a wave is the time it takes for one full wave to pass – that is, one complete cycle to pass. If the frequency of a wave is 10 Hz or 10 cycles per second, then 10 waves pass per

period
the length of time taken for one wavelength to pass a given point

second. It will then take $\frac{1}{10}$ second for one wave to pass. The period of the wave is $\frac{1}{10}$ second. Therefore, period (T) = $\frac{1}{\text{frequency}}$. 'Period' is from the Greek *periodos* = 'recurrence'.

$$\text{Period} = \frac{1}{\text{frequency}}$$

$$T = \frac{1}{f}$$

The wave equation

The velocity of a wave is measured using how far the wave travels in a certain time, or by using the wave characteristics (Figure 4). At one instant, point A will be at the origin as shown. One period later, A will be A'. This means that the wave has travelled a distance of one wavelength (λ) in one period of time (T). We know that distance divided by time is called velocity (v).

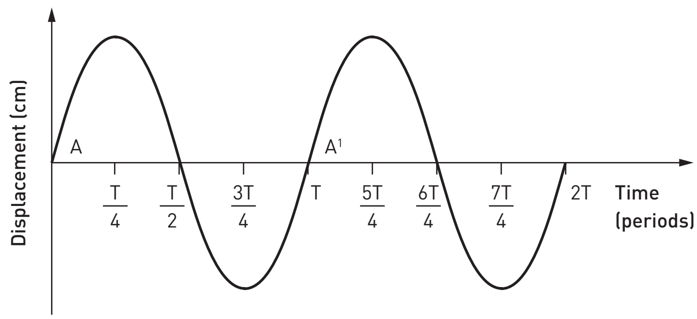


FIGURE 4 The propagation of a transverse wave with time

We can further replace $\frac{1}{T}$ with frequency (f) as developed before:

$$v = \frac{1\lambda}{T}$$

$$v = \frac{1}{T} \times \lambda$$

$$v = f\lambda$$

wave equation given by the formula $v = f\lambda$ that relates the velocity of a wave propagating through a medium to the frequency and wavelength of the disturbance

This is known as the **wave equation**, where v is the velocity of the wave in m s^{-1}, λ is the wavelength of the wave in m, and f is the frequency of the wave in Hz.

Wave equation:

$$v = f\lambda$$

The wave equation applies to all wave forms, both mechanical and electromagnetic.

WORKED EXAMPLE 14.2A

An observer sitting on the shore counts the waves and finds there are 6 waves per minute hitting the shore. The observer measures the distance between consecutive crests to be 10 m. What is the velocity of the waves?

SOLUTION

$$v = f\lambda$$

$$= \frac{6}{60}\ \text{Hz} \times 10\ \text{m}$$

$$= 1\ \text{m s}^{-1}$$

Graphing wave motion

Wave motion can be represented graphically in two ways: displacement–distance graphs and displacement–time graphs.

Displacement–distance graphs

Displacement–distance graphs (sometimes referred to as 'snapshots') represent the position of a wave at a certain time (Figure 5). It is like taking a photo of a wave. From this graph, the displacement (amplitude) and wavelength can be determined. If the position of the wave at another time is given, the characteristics of the wave that involve time, such as the speed and the frequency of the wave, can be calculated.

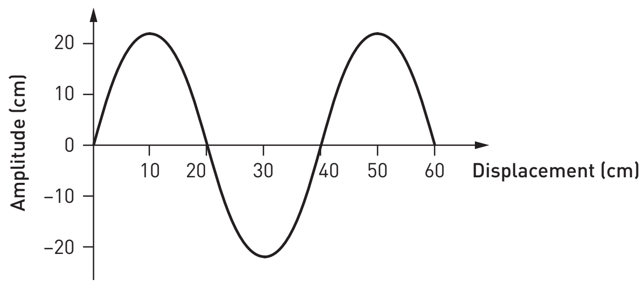


FIGURE 5 A displacement–distance graph for wave motion

WORKED EXAMPLE 14.2B

Use Figure 6 to answer the questions.

a Calculate the speed and frequency of the wave.

b Draw the wave after another 0.2 seconds.

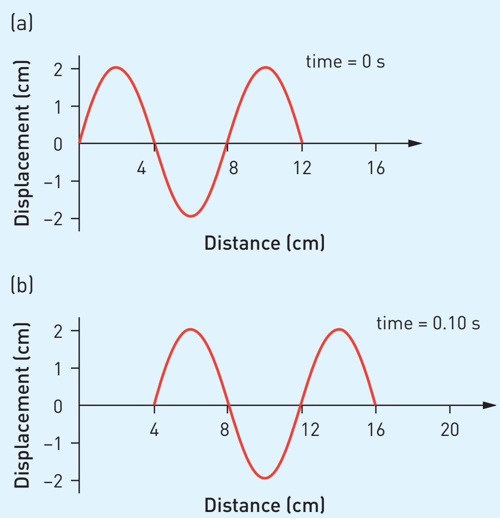


FIGURE 6 (a) The position of a wave at time zero; (b) the wave 0.10 seconds later

SOLUTION

a The wave has travelled a distance of 4 cm in 0.10 s. Therefore:

$$v = \frac{d}{t}$$
$$= \frac{4\ \text{cm}}{0.1\ \text{s}}$$
$$= 40\ \text{cm s}^{-1}$$
$$v = f\lambda$$
$$f = \frac{v}{\lambda}$$
$$= \frac{40\ \text{cm s}^{-1}}{8\ \text{cm}}$$
$$= 5\ \text{Hz}$$

b In 0.2 s the wave has moved another 8 cm to the right. See Figure 7.

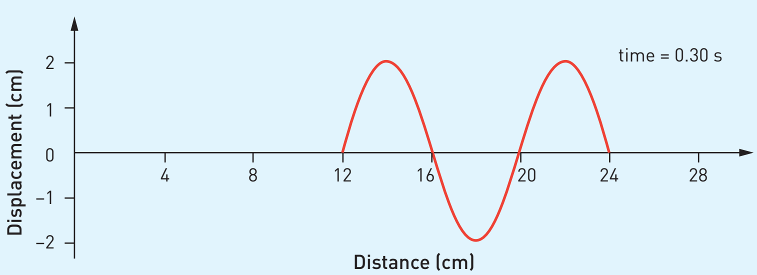


FIGURE 7 The wave after another 0.2 s

Displacement–time graphs

Displacement–time graphs (sometimes referred to as history graphs) indicate the position of the wave and also the position of a single point on the wave at certain times. This allows the velocity to be calculated.

WORKED EXAMPLE 14.2C

A wave is created on a spring as shown in Figure 8. The displacement of point P is given by the graph (Figure 9).

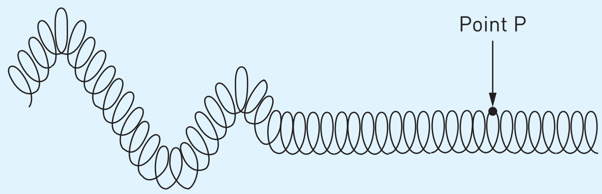


FIGURE 8 Imagine sending a wave down a Slinky towards point P.

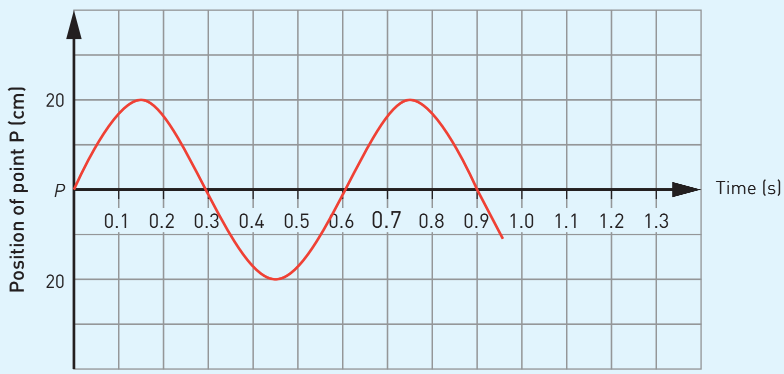


FIGURE 9 As time goes by, point P rises to a maximum then falls to a minimum and then back to a maximum, and so on

a Calculate the period of the wave.

b What is the amplitude of the wave?

c If the wave is moving at 5 cm s^{-1} to the right, what is the wavelength of the wave?

SOLUTION

a The wave repeats itself after (1.0 – 0.4) s, therefore the period is 0.6 s.

b Amplitude = 20 cm

c $v = f\lambda$

$\lambda = \frac{v}{f}$

$= v \times T$

$= 5 \text{ cm s}^{-1} \times 0.6 \text{ s}$

$= 3.0 \text{ cm}$

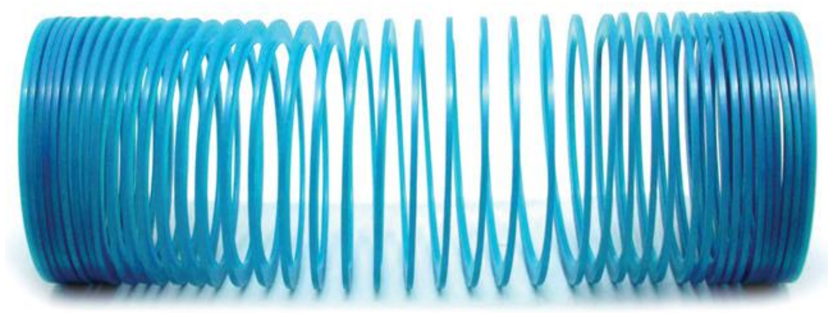


FIGURE 10 A Slinky

CHECK YOUR LEARNING 14.2

Describe and explain

1 **Define** wavelength, crest and frequency.

2 **Explain** what is meant by period.

3 **Describe** the wave equation.

4 The speed of light is 3.0×10^8 m s^{-1}. If the wavelength of red light is 5.0×10^{-7} m, **calculate** its frequency.

5 **Sketch** a displacement–time graph for point P on the string in the diagram in Figure 11.

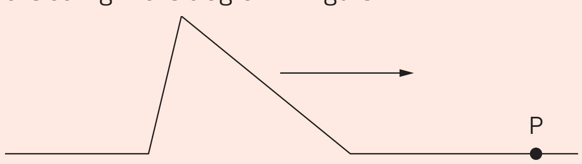


FIGURE 11 A wave crest approaches point P on a string

Apply, analyse and interpret

6 **Distinguish** between displacement–time and displacement–distance graphs.

7 Two students 5.0 m apart 'flicked' a spring to create waves. They found that when they flicked it twice per second, 10 wave crests were created between the two students. **Determine** the velocity of the waves.

8 **Determine** the frequency of the light emitted from a common laboratory red laser of wavelength 650 nm.

9 Figure 1 (page 382) shows a transverse wave. If this wave is travelling to the right, **determine** the direction of movement of points B, G, P, D and M at this time.

Investigate, evaluate and communicate

10 Figure 12 shows a displacement–time graph of a particle A on a particular spring.

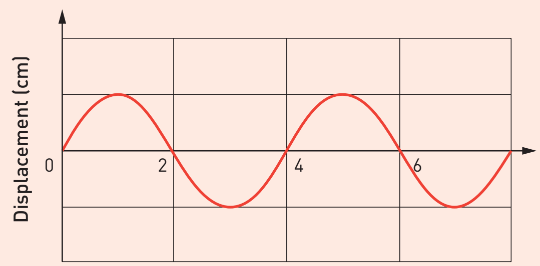


FIGURE 12 Displacement–time graph

a **Determine** the frequency of the wave.

b **Assess** the location of the particle at 3 s.

c Between 3 s and 4 s, **predict** whether the particle was moving towards or away from the equilibrium position.

Check your obook assess for these additional resources and more:

» Student book questions
Check your learning 14.2

» Challenge
14.2 Bubblegum

» Video
Wave characteristics

» Weblink
Wave characterstics

14.3 Waves and boundaries

KEY IDEAS

In this section, you will learn about:

+ speed changes in waves
+ reflection and transmission.

Speed changes

The speed of a wave is a characteristic of the medium in which it is moving. The speed of a wave changes when a wave moves from one medium to another. This can be seen in Table 1.

TABLE 1 Speed of waves in different media

Wave type	Medium	Speed ($m\ s^{-1}$)
Sound	carbon dioxide	259
	air	331
	hydrogen	1290
	pure water	1480
	salt water	1540
	glass (pyrex)	5640
	steel	5960
Light	vacuum	2.997×10^8
	air	2.988×10^8
	glass	2.0×10^8
Earthquake	crust	(transverse) 3500
		(longitudinal) 8000
	mantle	(transverse) 6500
		(longitudinal) 11 000

Reflection of waves in one dimension

What happens when a wave hits a barrier and bounces off, or goes from one medium to another? In this section we will consider waves in one dimension – waves on a spring. For example, what happens when a pulse sent down a spring reaches the other end? Waves and springs can be used to investigate this principle. The spring pulse is easier to visualise than light or sound waves. When a wave bounces off a material, this is referred to as **reflection**. When a wave passes through the boundary into the new medium, this is **transmission** (from the Latin *trans*- 'across' + *mittere* 'send'). The term we use for an approaching wave is an **incident wave**.

reflection
the process where incident waves at a boundary change direction returning into the same medium according to the law of reflection

transmission
the passage of a wave from one medium to another

incident wave
an approaching wave

Reflection of pulses from an end

Reflection from a fixed end

When a spring or a rope is laid on the floor and someone presses the end to the ground, this is called a fixed end. When a pulse (the incident pulse) is sent down the spring from the other end, the pulse is reflected. This means the pulse comes back along the spring.

The pulse comes back on the opposite side of the spring with approximately the same amplitude (Figure 1). The reflected pulse is said to be inverted, or out of phase, or 180° out of phase with the incident pulse. In maths, it would be out of phase by π radians. It is said to have undergone a reversal. The speed of the reflected pulse and the incident pulse will be the same, as the speed in a particular medium remains constant.

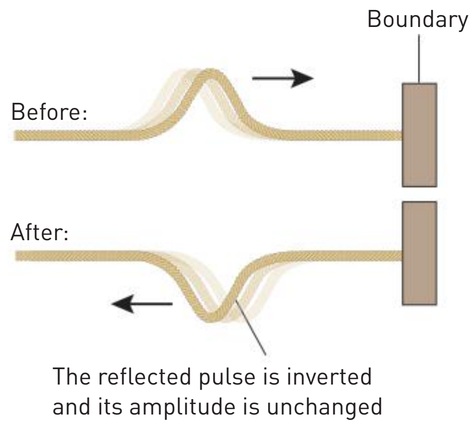


FIGURE 1 Reflection from a fixed end

Reflection from free ends

Reflection can also occur if the spring has a free end (not fixed to a wall or the floor). When reflection occurs from free ends, the pulse comes back on the same side as the incident pulse (Figure 2). A pulse reflects from a free end with no phase change. The amplitude should not have more than slight change.

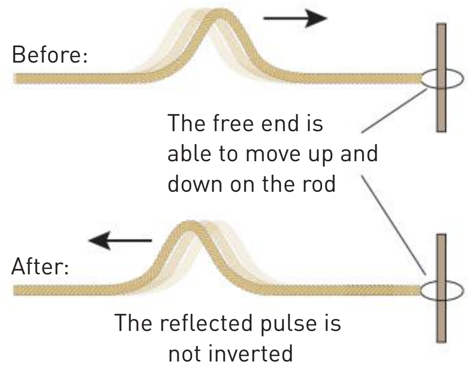


FIGURE 2 Reflection from free ends

CHALLENGE 14.3

Double explosions

A boat catches fire, and the skipper jumps overboard and swims away. The skipper hears an explosion while underwater. He lifts his head out of the water and hears another explosion. Bystanders say there was only one explosion, but the skipper says there were two. Who is correct? Explain.

FIGURE 3 Is it possible to hear two explosions?

Reflection from boundaries

We will now consider a wave that meets a boundary between two different springs. A **boundary** is a change in the media such as between springs of different weights, or an interface between two different materials such as a spring and the floor.

boundary
a change in the media such as between springs of different weights, or an interface between two different materials such as a spring and the floor

Heavy vs light springs

There are two main types of springs used in physics to demonstrate wave motion: the heavy spring and the light spring (the Slinky). Figure 3 shows the common pair used in school laboratories.

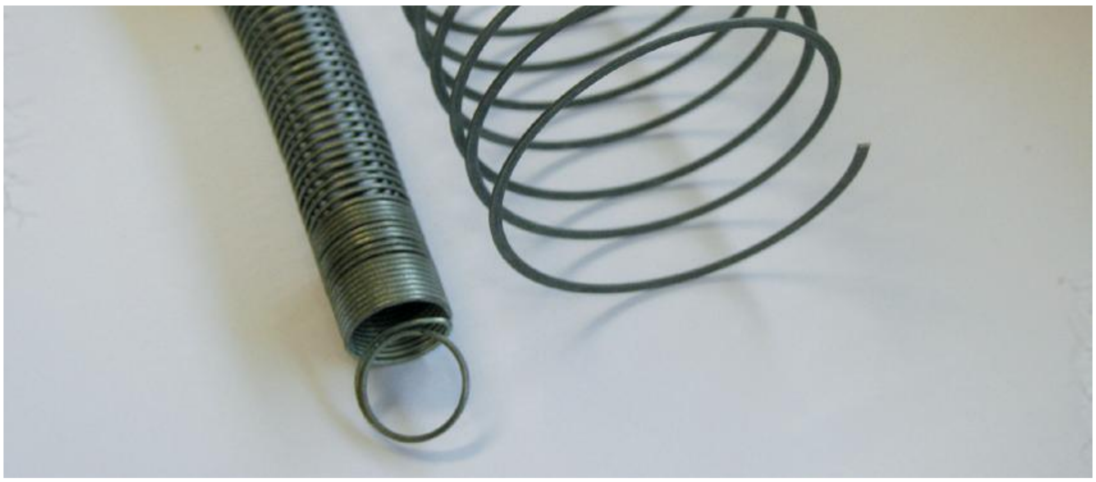


FIGURE 3 Heavy spring (left) and a Slinky (right) side by side

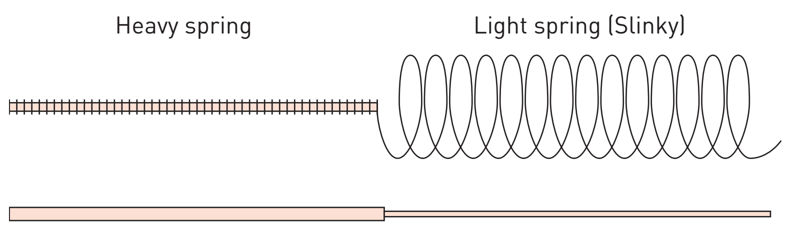


FIGURE 4 Heavy springs are drawn with a thick line whereas light springs (Slinky) are drawn as a thin line.

Lighter to heavier springs

A pulse that travels from a lighter (less dense) spring to a heavier (more dense) spring is shown in Figure 5. The pulse is inverted after reflection at the boundary. The transmitted pulse is not inverted.

When the pulse meets the boundary or join of the two springs, some of the pulse is transmitted and continues on into the more dense spring, and some of the pulse is reflected. At this point the transmitted pulse is upright, in phase or on the same side of the spring as the incident pulse. The reflected pulse is upside-down or out of phase. As far as the reflected pulse is concerned, the boundary is behaving like a fixed end.

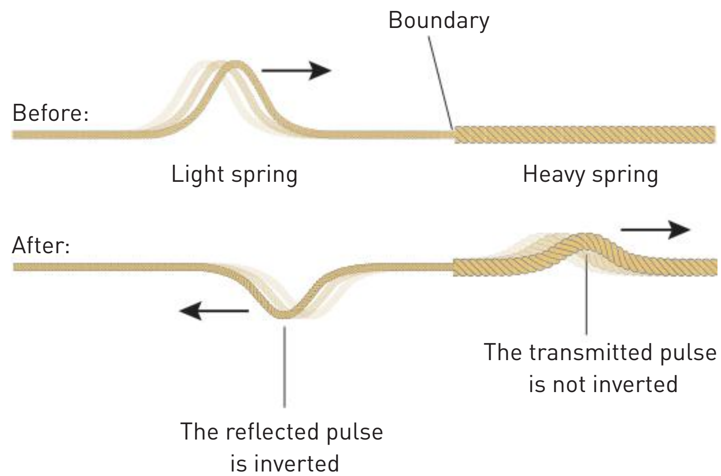


FIGURE 5 Waves going from a light spring to a heavy spring

Since the pulse has broken up, the amplitudes of both reflected and transmitted pulses are smaller than the incident pulse. The amplitudes of both reflected and transmitted pulse are determined by the relative densities of the two media. If the second medium is much heavier, the transmitted pulse will be small and the reflected pulse will be large. If the second medium is only a little more dense, the transmitted pulse will be larger and the reflected pulse will be smaller. The velocity of the transmitted pulse depends on the medium but will be less than the incident or reflected pulses. However, the velocity of the reflected pulses will be the same as the incident pulse as the pulses are travelling in the same medium.

Heavier to lighter springs

Figure 6 shows a pulse that travels from a heavier spring to a lighter spring. Both reflection and transmission occur in this scenario. Both the transmitted and reflected pulses will be seen on the same side of the spring as the incident pulse (in phase with the incident pulse). They are not inverted. The boundary is behaving like a free end as far as the reflected pulse is concerned.

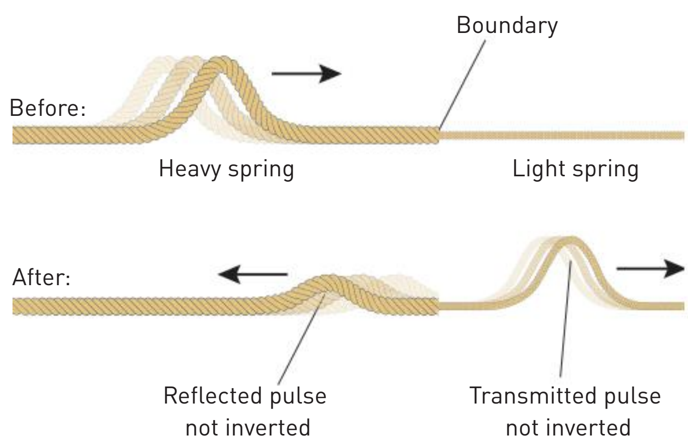


FIGURE 6 Waves going from a heavy spring to a light spring

angle of incidence
the angle between the normal and direction of propagation of an incident wave

In general, when waves go from a less dense to a more dense medium, the reflected pulse will be out of phase and the transmitted pulse will be in phase. When waves go from a more dense medium to a less dense medium, the reflected and transmitted pulses will both be in phase. This is summarised in Table 2.

TABLE 2 The phase relationships between reflected and transmitted pulses, with respect to the incident pulse when it meets various boundaries

Boundary	Reflected pulse	Transmitted pulse
Fixed end	out of phase	–
Free end	in phase	–
Light medium to heavy medium	out of phase	in phase
Heavy medium to light medium	in phase	in phase

Note: 'medium' means spring, water, etc.

This principle of reflection of waves is important when applied to musical instruments (such as open and closed wind instruments), explaining how DVDs work, and explaining why Christmas beetles' wings and soap bubbles are iridescently coloured.

Reflection of waves in two dimensions

angle of reflection
the angle between the normal and direction of propagation of a reflected wave

normal
a line perpendicular to a surface, barrier or boundary

reflected wave
the outgoing wave after reflection off a barrier

We have been describing waves in one dimension (in springs), but reflection also occurs for waves in two dimensions, such as in water. We can use a wave model to show how this occurs.

Consider the case of a transverse wave in water (Figures 7 and 8). When a line of crests (the wavefront) meets a fixed barrier, the reflected wavefront leaves at an angle equal to the **angle of incidence**. We show this by using an arrow representing the direction of propagation of the wavefront. Note that the **angle of reflection** is at right angles to the wavefront. The angle between the direction of propagation of the incident wave and the **normal** to the barrier ($\angle i$) is equal to the angle between the direction of propagation of the **reflected wave** and the normal ($\angle r$).

Law of reflection: the angle of incidence equals the angle of reflection.

$$\angle i = \angle r$$

FIGURE 7 Straight waves approaching from the left and being reflected from a barrier in a ripple tank

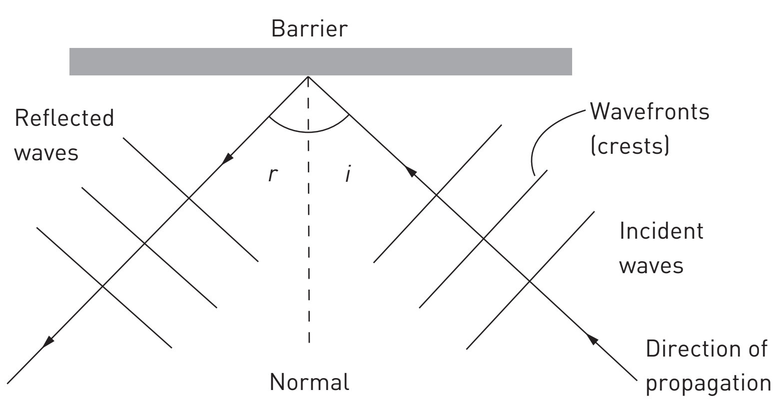


FIGURE 8 When a straight wave is reflected, angle *i* equals angle *r*.

CHECK YOUR LEARNING 14.3

Describe and explain

1 **Describe** a fixed end and a free end for a wave travelling on a spring.

2 **Explain** the difference between reflection and transmission.

3 **Sketch** and label a diagram to show phase relationships for a travelling wave after free-end and fixed-end reflection.

4 **Sketch** and label a diagram to show phase relationships for the transmitted and reflected waves at boundaries between:

- a heavy to light springs
- b light to heavy springs.

5 **Describe** the change of speed for a pulse going from:

- a a light to a heavy spring
- b a heavy to a light spring.

6 **Explain** whether the frequency of a travelling wave changes at a boundary when it is:

- a reflected
- b transmitted.

7 **Recall** the relationship between the angle of incidence and angle of reflection for a wave at a boundary.

Apply, analyse and interpret

8 **Clarify** what is meant by 'phase change on reflection'.

9 For water waves in two dimensions, **determine** how the direction of propagation relates to the wavefront.

10 A pulse seems to increase speed when it is going from one spring to another. **Apply** your understanding of speed, frequency and wavelength to deduce whether the pulse would be going from a light to a heavy spring, or the reverse.

11 A reflected wave from a fixed boundary will have less energy than before it was reflected. **Analyse** this situation and explain with justification how this affects the reflected pulse's wavelength, frequency, speed and amplitude.

Investigate, evaluate and communicate

12 Pulses are sent down from either end of a stretched spring with similar amplitudes. **Propose** how you could test if the pulses passed through each other and went to opposite ends, or if they just reflected off each other in the middle and returned to the same ends they started at.

13 A student tried to send a wave down a stretched spring on the floor but found it hard because it was carpeted. When the student tried again on a smooth vinyl floor, it was much easier to produce waves. **Assess** the differences in the floor surfaces and propose why this would affect the wave formation. You should conclude, with reasons, whether it is the frequency, wavelength, speed or amplitude that is affected.

Check your obook assess for these additional resources and more:

- Student book questions
  Check your learning 14.3
- Challenge
  14.3 Double explosions
- Video
  Reflection on a spring
- Video
  Standing waves on a spring

14.4 Superposition of waves

KEY IDEAS

In this section, you will learn about:

- intersection of pulses
- superposition of waves
- constructive and destructive interference
- standing waves.

There are many instances where one wave meets another. These situations can be natural or artificially produced. What happens when waves produced by two passing boats in the ocean cross over one another? Do they cancel each other out, resulting in the elimination of both waves? The intersection of two waves can be seen by producing pulses in a spring, one from each end.

In Figure 1, pulses are seen to add together when they pass over each other, producing a much larger, or smaller or differently shaped wave. The type of resulting wave depends on whether the pulses were produced on the same side or on opposite sides of the spring. However, once they have passed, they continue as though they had not met.

Figure 1 also shows the resulting pattern produced when two pulses intersect. If they are produced on opposite sides of the spring, **destructive interference** occurs – this produces a smaller wave or no wave at all at that instant. If the pulses are produced on the same side of the spring, **constructive interference** occurs – this produces a super-crest.

destructive interference
the interference of two or more waves of the same frequency and 180° out of phase with each other, superposing to produce a resultant wave with reduced amplitude

constructive interference
the interference of two or more waves of the same frequency and in phase with each other, superposing to produce an observable pattern in intensity

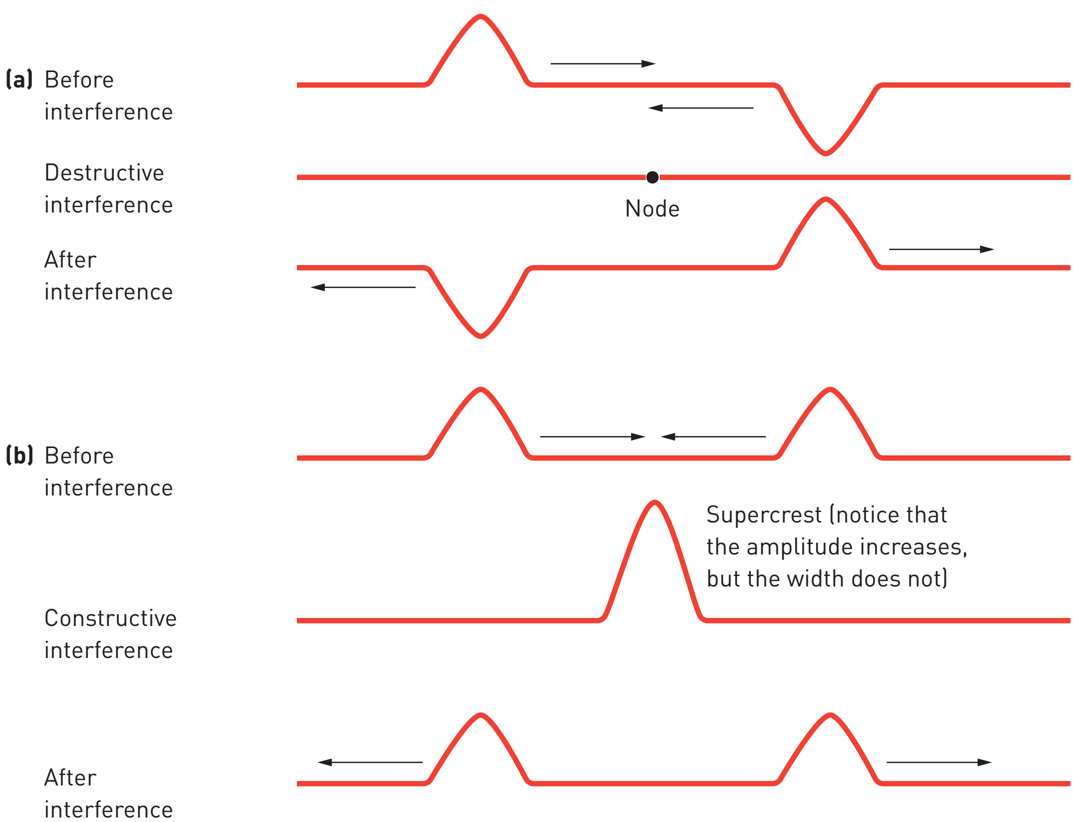


FIGURE 1 Superposition of waves may cause (a) destructive or (b) constructive interference.

Destructive interference is the interference of two or more waves of the same (or almost the same) frequency and 180° out of phase with each other – superposing to produce a resultant wave with reduced amplitude.

Constructive interference is the interference of two or more waves of the same (or almost the same) frequency and in phase with each other – superposing to produce a resultant wave with increased amplitude.

This process is called the principle of **superposition**. The resulting wave can be obtained by adding the pulses' displacements, from the equilibrium positions, at several points (Figure 2).

superposition when two or more waves overlap in space, the resultant wave is the algebraic sum of the individual waves

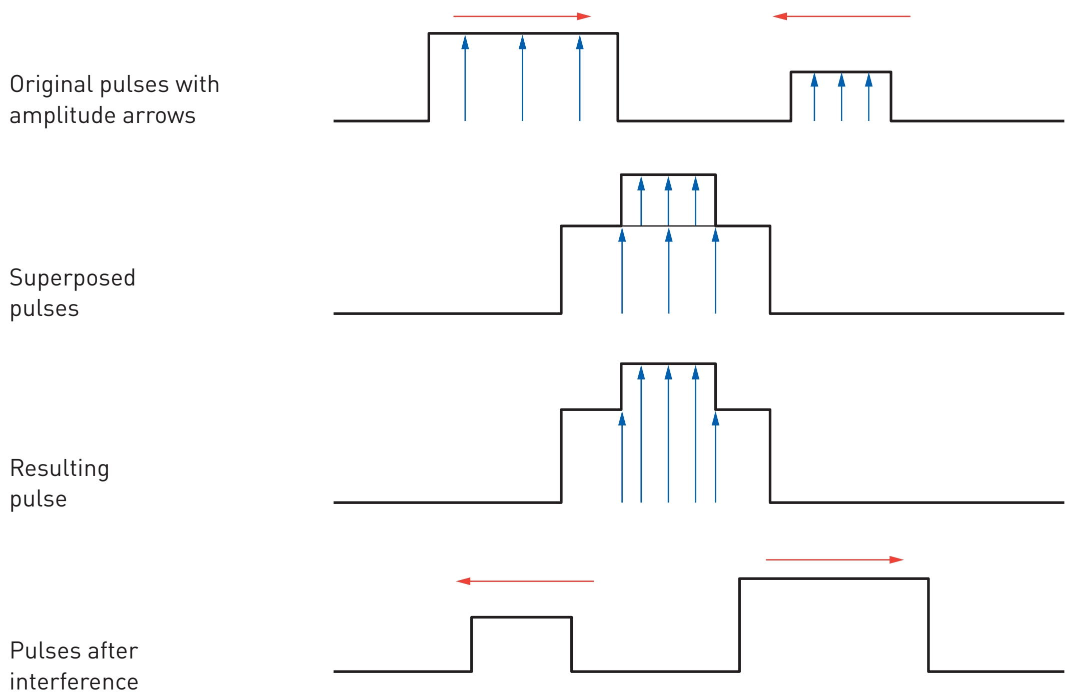


FIGURE 2 Superposition of two pulses

WORKED EXAMPLE 14.4

Construct the wave pattern produced when each of the two pulses shown in Figure 3 progresses five squares and they overlap.

SOLUTION

The diagram in Figure 4 shows pulse A moved 5 squares to the right and pulse B five squares to the left. We now add algebraically the displacements of pulse A and pulse B at each square where the two waves overlap. This produces the blue wave.

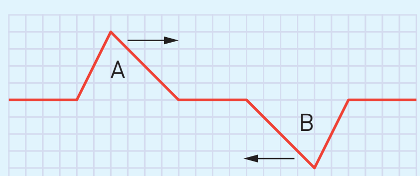


FIGURE 3 Two pulses, A and B

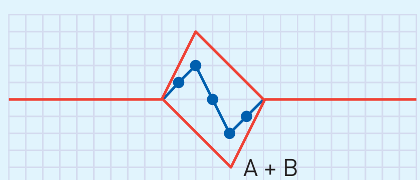


FIGURE 4 Superposition of the two waves produces the wave shown in blue.

Standing waves

standing waves
those with stationary vibration patterns formed due to the superposition of waves with particular frequencies

node
created by the interacting of a trough of one wave and a crest of another, producing a point of zero displacement

antinodes
result from the intersection of two crests or two troughs producing super crests and troughs

If a series of waves of the same amplitude and frequency are created from each end of a spring of the same amplitude and spring, a stationary wave or **standing wave** is created. This occurs because of the continued cancellations and additions of the waves as they travel along the spring and pass through each other.

When the first crests meet, they produce a pulse of twice the amplitude. A short time later (a quarter of a period), the pulses have moved so the crest of one is interacting with the trough of another, producing a point of zero displacement – a **node**. Another quarter of a period later, each pulse has moved another quarter of a wavelength and the two crests and two troughs again meet, producing super-crests and troughs called **antinodes**. The characteristic standing wave pattern is shown in Figure 5.

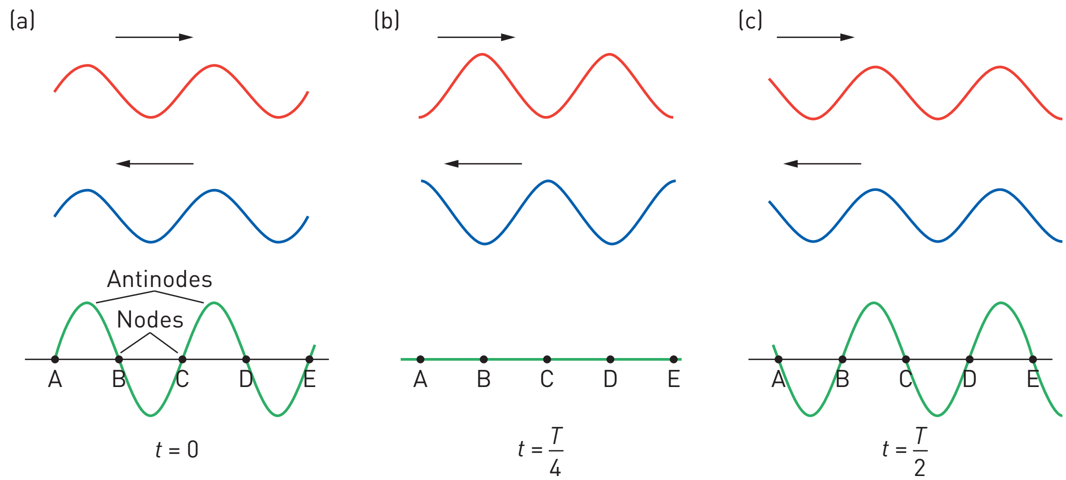


FIGURE 5 Two identical waves are sent along a spring from either end. The three lower diagrams shows the superposition of the waves when they first meet and overlap ($t = 0$) and then after they have progressed $\frac{1}{4}$ wavelength ($T = \frac{1}{4}$), and $\frac{1}{2}$ wavelength ($T = \frac{1}{2}$). The points A, B, C, D, E are nodes, and in between them are the antinodes.

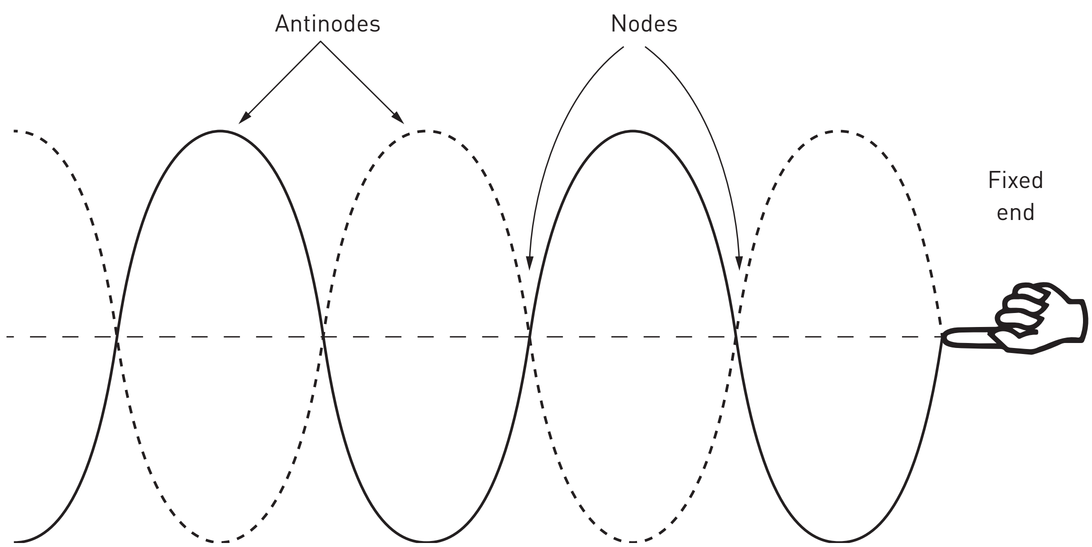


FIGURE 6 Standing waves formed by reflection off a fixed end. The wavelength is the distance between crests of either the solid line or the dotted line.

The distance between two successive nodes of a standing wave is a half of a wavelength.

Figure 6 shows a standing wave produced by the continual generation and reflection of waves off a point fixed (with your thumb) to the floor. Oscillation only occurs between the dashed and solid lines. Waves are sent down from the left and reflected back to the left. Because the end is fixed to the floor there is also phase inversion of the returning wave. Parts of the wave stay stationary (nodes) but other parts flip between maximum amplitudes on either side of the spring (antinodes).

Wave motion in sports equipment

There are several ideal contact spots on bats and racquets. One is the centre of percussion – the point that produces no jarring in the hand when a ball is struck. This point is a **nodal point** for standing waves in the equipment.

When a ball is hit with a tennis racquet, the racquet 'rings' as waves run up and down its length (Figure 7). The string node is just above the centre of the strings.

nodal point
a location along a standing wave where destructive interference occurs to produce a point of minimum amplitude

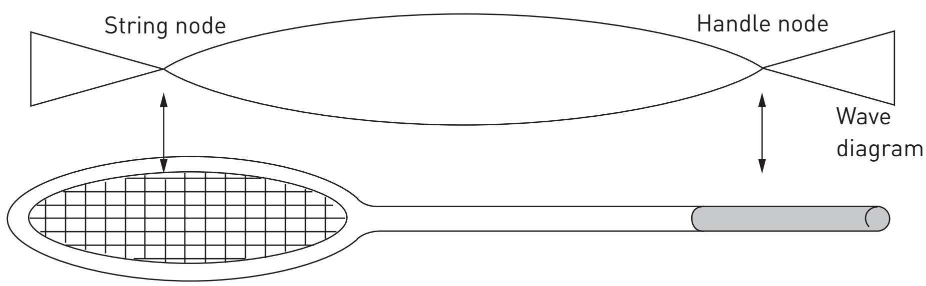


FIGURE 7 The string node of the standing wave is just above the centre of the strings.

FIGURE 8 When the ball hits the racquet at the nodal point, it is sometimes called hitting the 'sweet spot'.

CHECK YOUR LEARNING 14.4

Describe and explain

1 **Explain** superposition.

2 **Define** the terms 'node' and 'antinode'.

3 **Recall** the conditions that are necessary for standing waves to form.

Apply, analyse and interpret

4 **Distinguish** between constructive and destructive interference.

5 Two identical waves are produced on either side and either ends of a rope (Figure 9). **Deduce** what you would notice about point X as the waves move through.

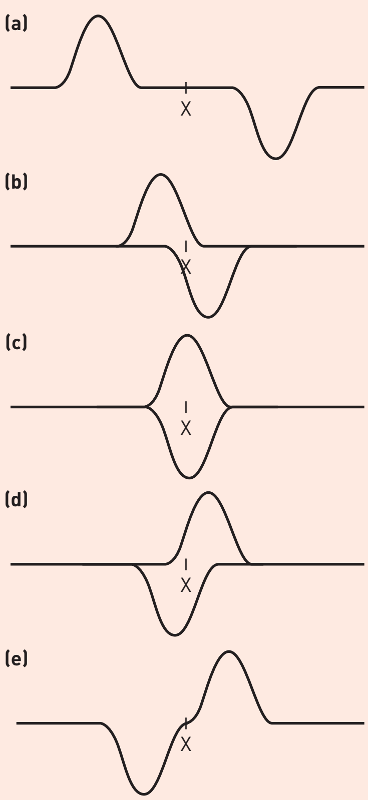


FIGURE 9 Two identical waves are produced on either side and either end of a rope.

6 Use the principle of superposition to **determine** the resulting pulse when the pulses shown in Figure 10 are superposed on each other.

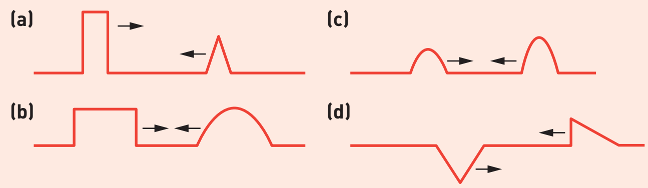


FIGURE 10 Determine the resulting pulse when the two pulses are superposed in each of these situations.

Investigate, evaluate and communicate

7 Two triangular pulses are travelling along a spring at 3 cm s^{-1} approaching each other from opposite directions. Each pulse has a wavelength of 12 cm and an amplitude of 4 cm. The moment when both pulses just touch is considered to be $t = 0$ s.

a **Interpret** the data and plot the shape of the spring at $t = 0$.

b **Deduce** and plot the shape at $t = 0.5$ s.

c **Deduce** and plot the shape at $t = 1$ s.

d **Justify** with evidence whether this is an example of constructive or destructive interference.

Check your obook assess for these additional resources and more:

» Student book questions
Check your learning 14.4

» Weblink
Interference

» Weblink
Waves in sport

» Weblink
Superposition

14.5 Refraction and diffraction of waves

KEY IDEAS

In this section, you will learn about:

- refraction of waves from one medium to another
- diffraction of waves as they pass through a slit.

Two properties of waves are commonly seen in nature: refraction and diffraction. They both occur in two dimensions so can't be shown on a spring. They need a medium in which they can move in two dimensions and are best demonstrated in water and air.

Refraction

refraction
the process when incident waves at a boundary change direction and speed when passing into another medium

Refraction is the changing in direction and speed of waves as they go from one medium to another. For example, water waves can undergo refraction when they travel from one depth of water to another, as this acts as two different mediums. Another example is light undergoing refraction when light rays pass from air to water, from air to glass or from glass to water.

The term refraction comes from the Latin for 'break', referring to the broken (bent) path waves take as they pass from one medium to another.

Deep to shallow water

When a wave hits the boundary between two depths of water at an angle, it changes direction. Deep and shallow water act as two different media, even though they are the one substance. The speed of waves in shallow water is slower than in deep water, so refraction can occur. Because frequency remains the same after passing from one medium to the other, the wavelength must get smaller – as speed decreases, wavelength must also decrease.

Figure 1 shows an overhead view of a ripple tank. It has a tray of water of 1 cm depth and a piece of submerged plastic over which the water is 0.4 cm deep. The water waves in deep water are moving from the left and strike the shallow water above the plastic shape. Note that the waves appear to be bent. This is because their reduced velocity causes them to lag behind the deep water waves. Note that the wavelength is also reduced. This change in depth has caused bending, which is called refraction.

Information about the bending of light as it passes from water to air can be found on your obook assess.

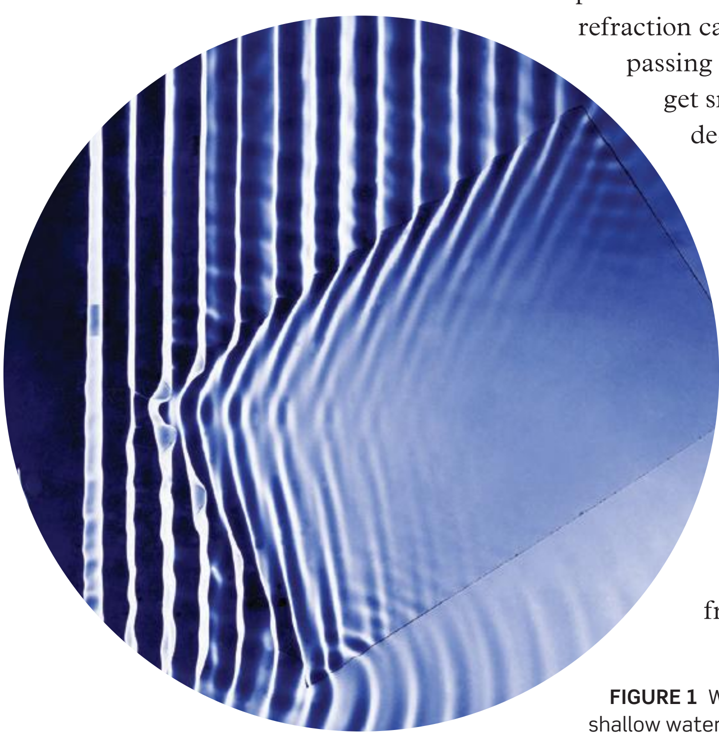


FIGURE 1 Waves going from deep water (left) to shallow water (over the glass block) refract.

Study tip

Students find the '4-S' rule useful here: shallow (depth), short (wavelength), slow (speed) and small (angle) all go together.

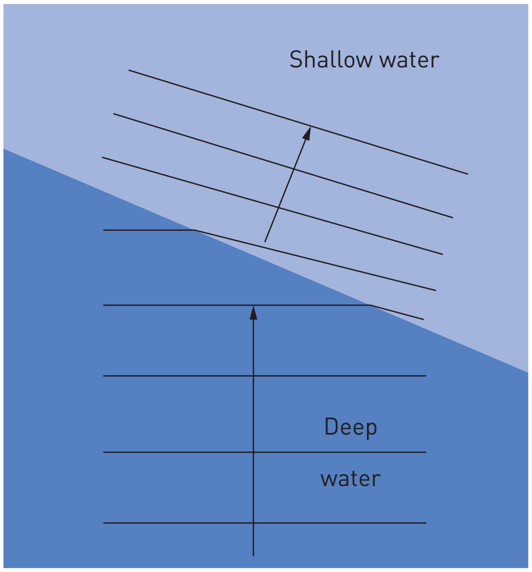


FIGURE 2 Refraction is the change in direction and speed of incident waves at a boundary when passing into another medium

CHALLENGE 14.5

Is this refraction?

Light travelling from distant stars generally travels in straight lines. Einstein predicted 100 years ago that light from distant stars could be bent by a strong gravitation field, such as when it passed massive stars, galaxies or black holes. This is known as 'gravitational lensing' and has been confirmed numerous times. Deduce whether it is correct to call this an example of refraction, as the light is bent. Conclude, with evidence, whether it meets the full definition of refraction.

Diffraction of water waves

Another property of waves is often observed when waves from the ocean enter an inlet. These waves form a circular pattern. Figure 3 shows an example of **diffraction** of water waves as they pass through gaps in the rocks.

diffraction
the process by which waves either bend behind a barrier or the wavefront is broken up into many small sources

FIGURE 3 Diffraction of ocean waves in the sea seen along the coastline near Pesaro, Italy.

This diffraction can also be seen in a ripple tank by placing two large blocks of glass or metal obstacles to produce a slit (also called an aperture) in front of the straight waves. As the waves pass through the slit, they produce a circular wave (Figure 4). This bending of waves as they pass through a slit is called diffraction, from the Latin *diffractus* meaning 'to break apart'. Similar bending occurs if waves pass around the end of an obstacle.

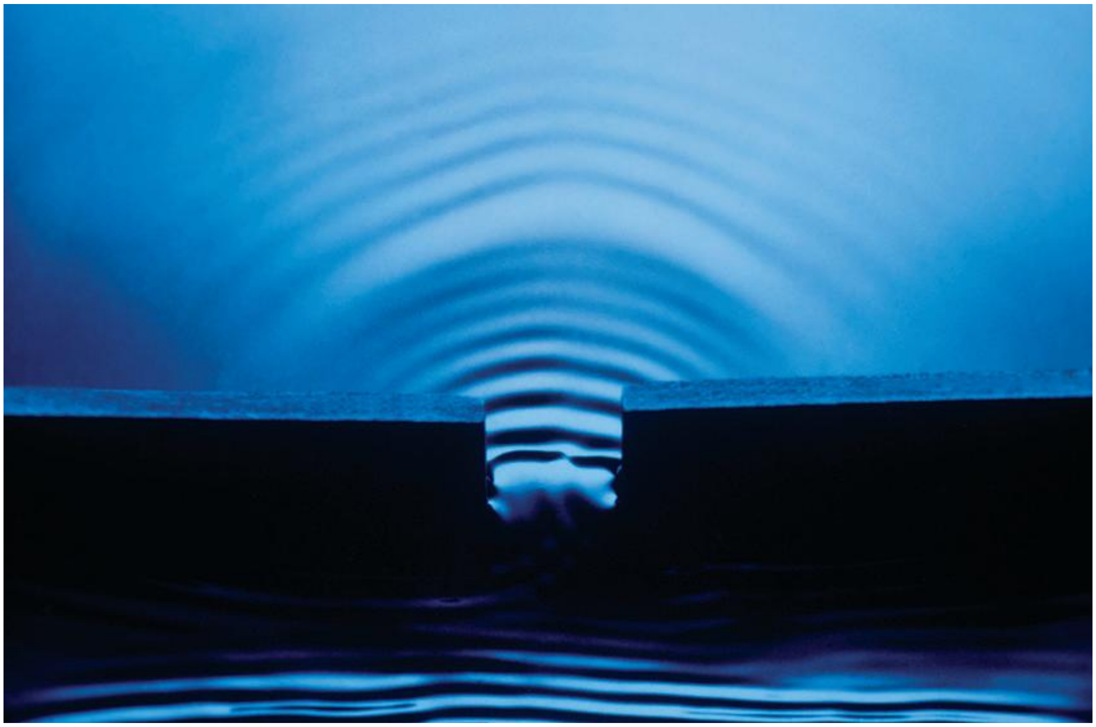


FIGURE 4 Straight waves passing through a small opening in a barrier in a ripple tank are diffracted

Diffraction can be explained by imagining that the straight wavefront enters the slit and is broken up into many small sources called 'wavelets'. This continues to occur as the wavefront travels outward. The envelope enclosing the wavelets adds to produce a straight wave in the centre, but the edges remain curved. The wave curves around the slit's edges, as shown in Figure 5.

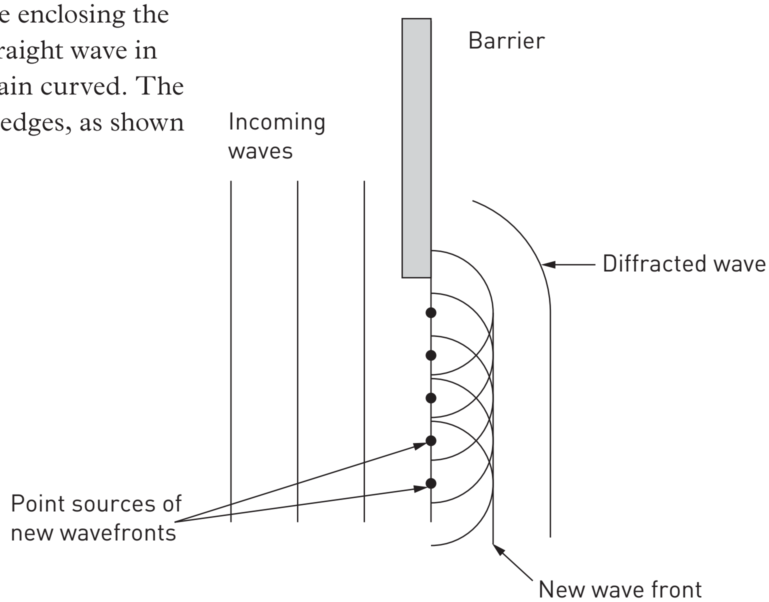


FIGURE 5 Diffraction of a wave at an edge.

Changing the slit width

If the aperture (the opening/slit) is small compared with the wavelength of the waves, the shape of the waves passing through the aperture will be more curved. If the aperture is large, the resulting waves will be straighter except for the edges. This can be seen in a ripple tank by changing the position of the obstacles making up the slit (Figure 6).

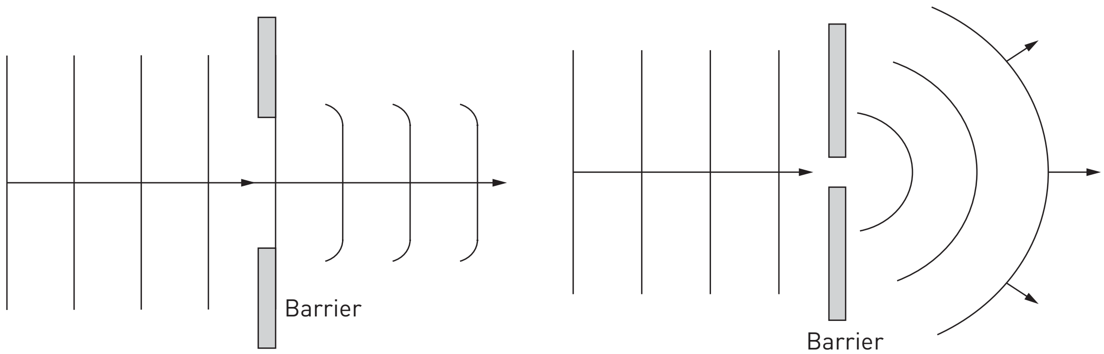


FIGURE 6 Diffraction is more noticeable when the size of the slit is comparable to the wavelength of the waves – a smaller slit produces more diffraction than a large slit.

Changing the wavelength

Changing the wavelength of the waves also affects the diffraction pattern. Diffraction is more noticeable if a wavelength is equal to or greater than the opening. It is the relative difference in the size of the wavelength and the size of the slit that is important (Figure 7).

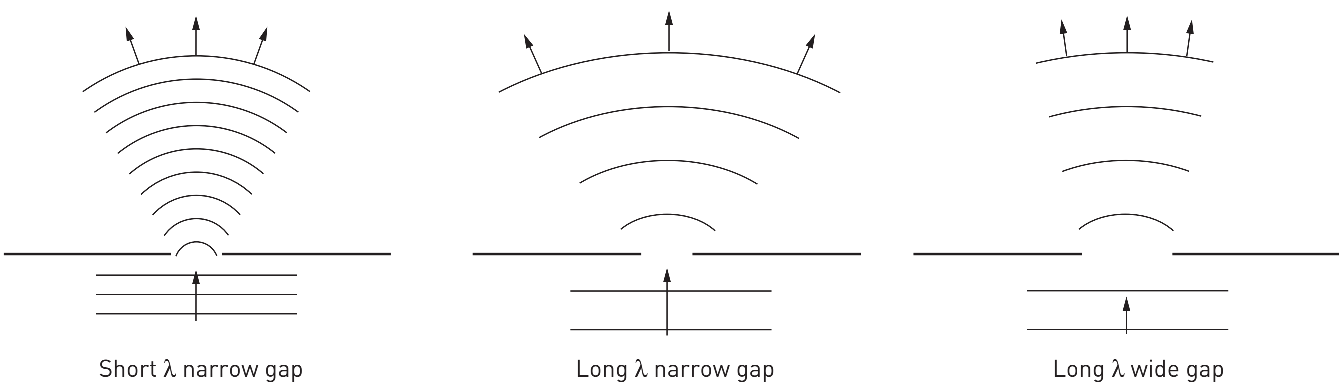


FIGURE 7 Diffraction is greater when the wavelength is large and the gap narrow.

A diffraction pattern can be observed in the ocean around boats, large rocks and buoys. The amount of diffraction depends on the size of the object compared with the wavelength. If the object is large compared with the wavelength, a significant diffraction pattern occurs around the edges of the object, producing a shadow zone. There is no change to the wavelength as the wave passes through the gap, which means the velocity does not change either.

FIGURE 8 The moving boat is producing a wake which causes waves.

CHECK YOUR LEARNING 14.5

Describe and explain

1 **Explain** which opening in a barrier – a 4 cm gap or a 2 cm gap – would produce the larger diffraction with a 3 cm wavelength water wave.

2 **Explain** whether direction, speed, frequency or wavelength change when refraction occurs.

3 **Describe** what changes the amount of refraction of a water wave.

4 **Recall** the conditions under which diffraction occurs.

5 **Recall** whether the speed, frequency or wavelength changes for diffraction.

6 **Sketch** a water wave diffracting through a gap between two rocks.

Apply, analyse and interpret

7 **Clarify** what the terms short, slow, small and shallow refer to in the 4-S rule.

8 **Clarify** the conditions under which refraction occurs.

9 **Clarify** under what conditions a water wave refracts.

10 Water waves are seen to strike a 75 cm gap in some rocks at a speed of 2.5 m s^{-1} and undergo diffraction. **Determine** the frequency of these waves if the wavelength equals the width of the gap.

11 Figure 9 shows a water wave refracting at a boundary where it enters water of different depth.

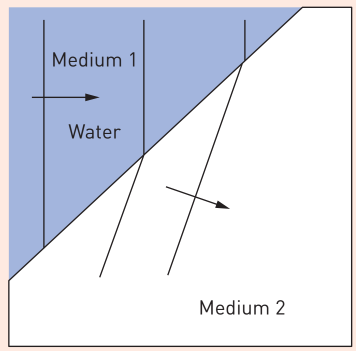


FIGURE 9 A water wave refracting at a boundary where it enters water of different depth

Deduce whether medium 2 is shallower or deeper than medium 1 (the water on the left).

Investigate, evaluate and communicate

12 AM radio waves have wavelength of about 400 m, whereas the wavelength of FM radio is about 3 m. **Propose** why AM radio waves can be heard behind hills whereas FM cannot.

13 When a wave refracts, there is no change in frequency. Use the wave equation to **predict** the velocity of a refracted wave if its incident speed is 30 cm s^{-1} and wavelength 3 cm, if its refracted wavelength is 2 cm.

Check your obook assess for these additional resources and more:

» Student book questions
Check your learning 14.5

» Challenge
14.5 Is this refraction?

14.6 Earthquakes and tsunamis

KEY IDEAS

In this section, you will learn about:

- energy transfer in waves
- seismic waves as examples of transverse and longitudinal waves.

Earthquakes are unpredictable and can have a devastating impact over a wide area. Earth's surface is made up of tectonic plates that can move in a horizontal and vertical pattern. Surface forces can cause these plates to rub together, and the friction generated can release a huge amount of energy that causes a seismic wave.

Earthquakes are basically sound waves travelling in Earth's crust. They travel at different speeds depending on the type of waves and the composition of the material they pass through. Earthquakes produce both longitudinal and transverse waves, and these travel at different speeds. In rock, for example, the speed of longitudinal or pressure waves (P-waves) is higher than the speed of transverse or shear waves (S-waves).

FIGURE 1 Earthquakes can produce devastating tsunamis. Though they may travel at speeds over 800 miles per hour, tsunamis are hard to visually detect in the deep ocean.

Both types of earthquake waves travel slower in less rigid material such as sand and mud. P-waves have speeds of 4 to 7 km s^{-1}, and S-waves from 2 to 5 km s^{-1}, but both are faster in more rigid material. Thus, the P-wave gets progressively further ahead of the S-wave as they travel through Earth's crust. The time between the P-waves and S-waves is measured with a device called a seismometer, which can be used to calculate the distance to the source of the earthquake.

A seismograph (from Greek *seismos* = 'shaking') measures the arrival time of an earthquake to the nearest 0.1 s. To get the distance to the epicentre of the quake, a seismograph compares the arrival times of P-waves and S-waves, which travel at different speeds. Knowing the speeds of P-waves and S-waves, scientists can measure the distance to the source of the earthquake to an accuracy of under a kilometre.

When Earth's tectonic plates grind past each other, large earthquakes result. An earthquake lifts or sinks the ocean floor over large areas and produces destructive tsunamis. The waves can travel great distances causing destruction as they go. For example, the 1960

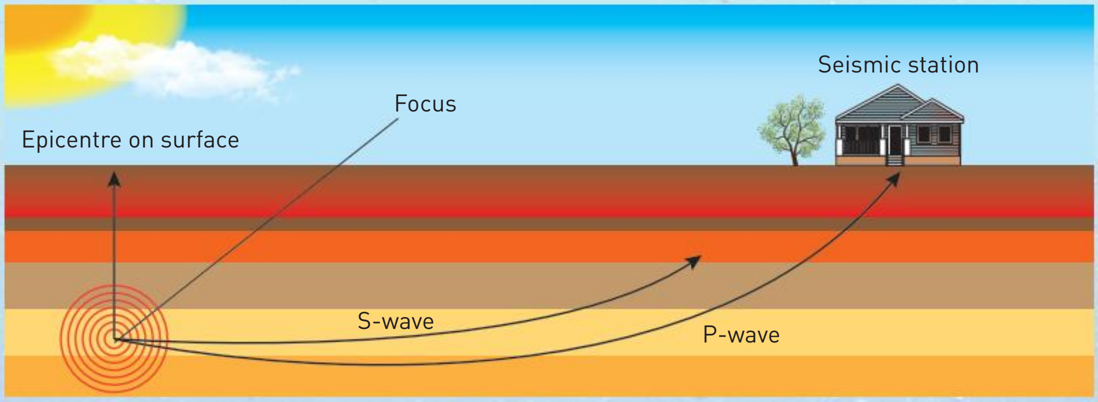


FIGURE 2 The seismic station records the arrival of the different waves

Chilean earthquake caused huge destruction in Chile, but also as far away as Hawaii, Japan and elsewhere in the Pacific. However, not all earthquakes produce tsunamis. If an earthquake has a Richter magnitude under 7.5, it is unlikely to generate a tsunami.

Early warning systems

Early warning of earthquakes and tsunamis can help save lives. The National Oceanic and Atmospheric Administration in the United States has recorders in the Pacific Ocean. Once an earthquake is detected, it sends warnings to areas that may be affected.

In 2004, a devastating earthquake in the Indian Ocean and the resulting tsunami left 230 000 people dead or missing. Many scientists claimed the effects of the disaster could have been reduced if an early-warning system was in place, such as the well-established Pacific Tsunami Warning Center that looks after the Pacific Ocean.

Many nations around the Indian Ocean agreed to the construction of the Indian Ocean Tsunami Warning System, which became active in 2006. It consists of 25 seismographic stations and various floating sensors. When an earthquake of 8.4 magnitude struck Banda Aceh in Indonesia in 2012, the system alerted neighbouring islands within 8 minutes of a possible tsunami and proved very successful. Australia, Indonesia and India are responsible for leading the tsunami warning system in the area.

CHECK YOUR LEARNING 14.6

Describe and explain

1 **Explain** in a few sentences how a tsunami early-warning system works.

2 **Calculate** the time interval for a P-wave travelling at 5 km s^{-1} and an S-wave travelling at 3 km s^{-1} over a distance of 600 km.

Apply, analyse and interpret

3 **Compare** the two types of seismic waves in terms of wave type and speed.

4 Seismic waves travel very fast, up to 14 km s^{-1}. **Determine** how long it takes a seismic wave at this speed to reach the other side of Earth, a distance of almost 13 000 km.

5 When earthquakes occur, they create waves that spread outward from the source. Three types of waves occur:
- P-waves (primary), which are caused by the back and forth movement of rocks
- S-waves (secondary), which travel as a result of the up and down movement of rocks
- L-waves, which are ripples that travel on the surface and are set up when the P and S waves reach the surface. The L-waves cause rocks to vibrate in an up and down motion.

   a **Identify** the type of waves that are P-, S- and L-waves.

   b Earthquake waves have a wavelength of 10 m and a speed of 3.0 km s^{-1}. **Determine** their frequency.

Investigate, evaluate and communicate

6 'We can't stop earthquakes, so we should not bother monitoring them.' **Propose** two arguments supporting this claim and two counter-arguments.

Check your obook assess for these additional resources and more:

» Student book questions
Check your learning 14.6

» Video
Tectonic plates

» Weblink
Tsunamis

» Weblink
Continents in collision

CHAPTER 14

Review

Summary

14.1
- Mechanical waves require a medium for travel whereas electromagnetic waves do not.
- When waves travel through a medium, the particles of the medium vibrate either at right angles (transverse waves) or parallel (longitudinal waves) to the direction of propagation.

14.2
- In transverse waves, the top of the wave is called the crest and the bottom is called the trough. The distance between two consecutive crests, or troughs, is the wavelength (λ).
- Points in phase on a wave are any two points vibrating in the same direction at the same time. A crest and a trough are $\frac{1}{2} \times \lambda$ out of phase.
- Longitudinal waves have compressions and rarefactions. The region of minimum particle density is called the rarefaction. The wavelength is the distance between two consecutive compressions or rarefactions.
- The amplitude of a wave is the maximum displacement from the equilibrium or rest position and is a measure of the energy carried by the wave.
- The frequency (f) is the number of waves generated, or passing a given point, per second.
- The period (T) of a wave is the time for a wave to pass a point, $T = \frac{1}{f}$.
- The wave equation $v = f\lambda$ is used to determine the speed of a wave.

14.3
- Waves reflected from fixed ends are reflected out of phase with the incident wave.
- Waves reflected from free ends are reflected in phase with the incident waves.
- When waves meet at the junction between two media, they are transmitted and reflected. The transmitted wave is always in phase with the incident pulse. The reflected pulse is out of phase with the incident pulse, while the speed of the transmitted pulse depends on the medium.

14.4
- Superposition occurs when two waves meet. The resulting wave is obtained by adding the displacements of various points on the two waves.
- Stationary waves are created by superposition of a series of waves, having the same amplitude and frequency, and coming from the different ends of a medium. The continual addition and cancellation of the waves produces the standing wave pattern containing nodes and antinodes.
- Nodes are points of zero disturbance, and antinodes are points of maximum disturbance.

14.5
- Refraction is the change in direction and speed of a wave when it passes from one medium to another.
- When waves reflect off a barrier, the angle of incidence equals the angle of reflection.
- When a wave travels from one medium to another, its velocity and wavelength change but its frequency remains the same.
- Diffraction is the bending of waves as they pass through a slit or around objects.
- Diffraction is most noticeable when the size of the aperture is less than or comparable to the wavelength of the wave.

Key terms

- amplitude
- angle of incidence
- angle of reflection
- antinodes
- boundary
- compression
- constructive interference
- crest
- destructive interference
- diffraction
- direction of propagation
- displacement
- dissipates
- disturbance
- electromagnetic wave
- equilibrium
- frequency
- incident wave
- longitudinal wave
- mechanical wave
- nodal point
- node
- normal
- period
- phase
- pulse
- rarefaction
- reflected wave
- reflection
- refraction
- standing wave
- superposition
- transmission
- transverse waves
- trough
- wavelength

Key formulas

Wave equation	$v = f\lambda$
Period of a wave	$f = \frac{1}{T}$

Revision questions

The relative difficulty of these questions is indicated by the number of stars beside each question number: * = low; ** = medium; *** = high.

Multiple-choice

1 The graph below is a displacement–position graph of a transverse wave travelling from left to right. Which arrow represents the direction of the velocity of the particle marked P?

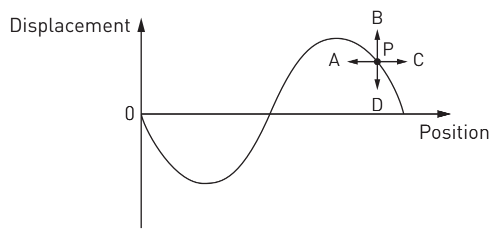


FIGURE 1 Displacement–position graph of a transverse wave travelling from left to right

A arrow A
B arrow B
C arrow C
D arrow D

2 Particles of a medium are vibrating in the same direction as energy transport. This is characteristic of which sort of wave?

A longitudinal
B electromagnetic
C standing
D transverse

3 Figure 2 shows a displacement–position diagram of a wave.

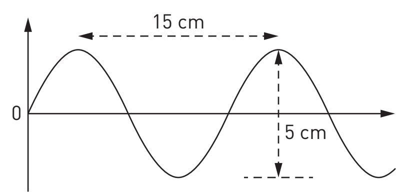


FIGURE 2 Displacement–position diagram of a wave

The amplitude of the wave is:

- **A** 2.5 cm
- **B** 5 cm
- **C** 7.5 cm
- **D** 15 cm

4 A heavy spring and a light spring are joined together as shown in Figure 3. A pulse is generated at the end of one spring and travels along towards the boundary. At the boundary, some of the energy is transmitted and some reflected. Which one of the diagrams below shows the position and orientation of the pulse shortly afterwards?

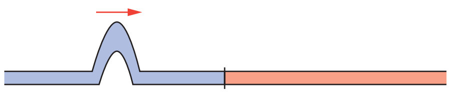
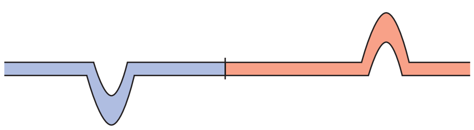
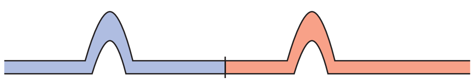
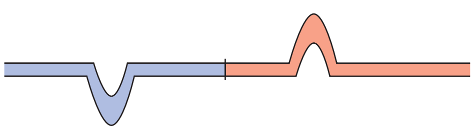
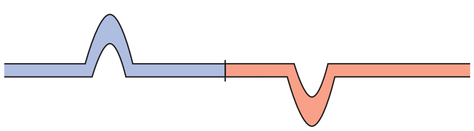


FIGURE 3 A pulse approaching a boundary

A


B


C


D


5 A node is a point located along the medium where there is always:

- **A** a crest of double height.
- **B** half height.
- **C** constructive interference.
- **D** destructive interference.

Short answer

Describe and explain

★ **6** **a** **Explain** what happens to the mass per unit length (metre) of a Slinky when it is stretched.

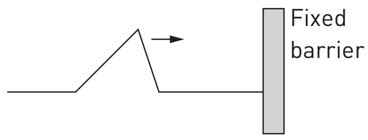
b **Explain** what happens to the speed of a pulse in a Slinky spring if the spring is stretched.

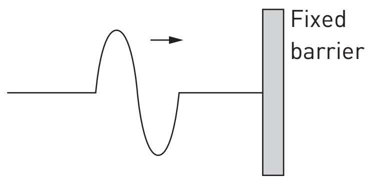
★ **7** **Explain** the difference between a longitudinal and a transverse wave without using the word 'propagation' but explaining it instead.

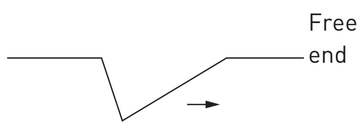
★★ **8** The speed of sound in salt water is 1450 m s^{-1}, and it is 340 m s^{-1} in air. If the frequency of the sound being generated by a motor boat engine is 550 Hz, **calculate**:

- **a** the wavelength of the sound in air
- **b** the frequency of the sound in salt water
- **c** the wavelength of the sound in salt water

★★ **9** **Sketch** diagrams to illustrate the reflected pulses in the four situations shown in Figure 4. Each pulse is created in a rope.

(a)


(b)


(c)


(d)


FIGURE 4 Reflected pulses

★★ **10** Figure 5 represents the displacement of particles in a rope with time as a wave passes.

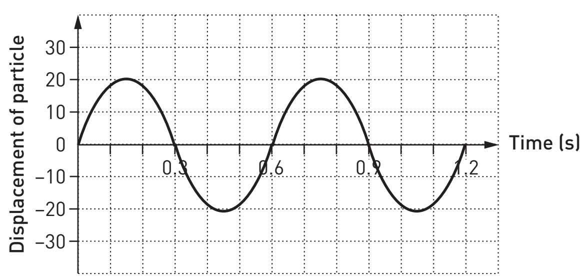


FIGURE 5 Displacement–time graph of a wave

Calculate:

- **a** the amplitude of the wave
- **b** the period of the wave
- **c** the frequency of the wave.

Apply, analyse and interpret

★ **11** **Consider** a dinghy anchored in the ocean that is seen to bob up and down as waves pass.

a **Deduce** the type of waves they are and explain your reasons.

b **Identify** the physical feature of the wave that indicates the energy the wave possesses.

★ **12** **Distinguish** the particular type of wave where the particles move:

a at right angles to the direction of propagation

b in the same direction as the wave is moving.

★★ **13** Figure 6 shows the position of a wave at two instants in time.

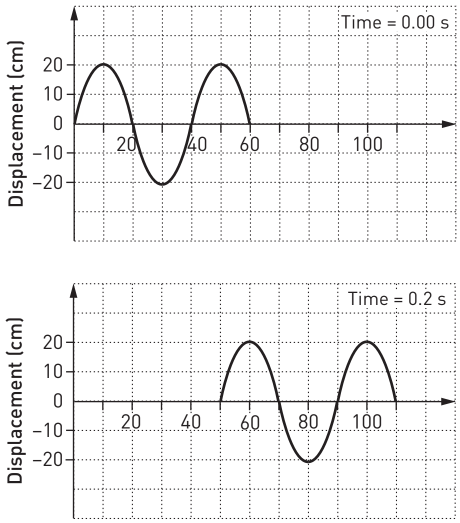


FIGURE 6 Position of a wave at two instants in time

From these graphs, **determine:**

a the amplitude of the wave

b the wavelength of the wave

c the velocity of the wave.

Investigate, evaluate and communicate

★★ **14** Two weekend anglers find that their 4 m boat bobs up and down 3 times in 20 seconds, and exactly 3 wave crests can fit under the boat at any one time. **Determine** the velocity of the waves. Does it sound as though the anglers were catching any fish?

★★ **15** Figure 7 shows a wave in the same section of a string at two different times. **Justify** the greatest possible period of the wave.

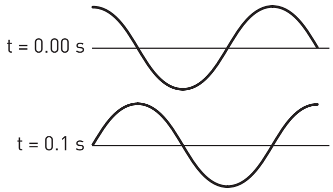


FIGURE 7 A wave in the same section of a string at two different times

★★★ **16** Figure 8 illustrates a pulse moving to the right along a stretched spring at a speed of 5.0 m s^{-1}.

a **Decide** which of the points (A–C) has the greatest speed at this instant.

b **Calculate** the instantaneous velocity of point C.

c **Sketch** the displacement–time graph and the velocity–time graph for point X on the spring. Take the zero for time at the instant shown in the graph.

d **Propose** why this particular situation is very unlikely.

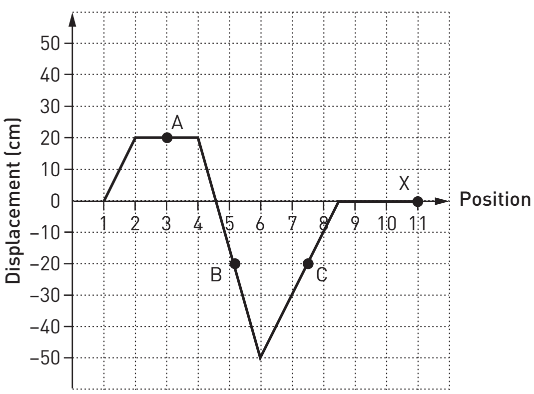


FIGURE 8 Diagram representing a pulse moving to the right along a stretched spring at 5.0 m s^{-1}

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Chapter 14 revision questions

» Revision notes
Chapter 14

» assess quiz
Auto-correcting multiple choice quiz

» Flashcard glossary
Chapter 14

CHAPTER 15

Sound

Opera singers are rumoured to be able to shatter a glass with their voice. This seems unlikely as it has to be an impossibly loud sound, but it can be done with amplified sound from a loudspeaker. Sound is a form of energy that travels from the source to the receiver by means of waves. Sound waves are longitudinal mechanical waves – waves that require a medium for transmission.

OBJECTIVES

→ Solve problems involving standing wave formation in pipes open at both ends, closed at one end and on stretched strings.
→ Define the concept of resonance in a mechanical system.
→ Define the concept of natural frequency.
→ Identify that energy is transferred efficiently in resonating systems.

Source: *Physics 2019 v1.2 General Senior Syllabus Queensland Curriculum & Assessment Authority*

MAKES YOU WONDER

In this chapter you will learn about concepts of sound that will help to answer questions such as:

→ Can you hear spaceships explode in space?
→ Why does light travel faster than sound?
→ When you make 'straw clarinets' from plastic drinking straws, why do you have to cut one end into a small flexible V-shape?
→ Would it be possible to play *Mary Had a Little Lamb* on test tubes filled with differing levels of water?
→ When pushing a child on a swing, is there a right time to give the push?
→ When you speak, your voice only carries a certain distance – where does all the sound energy go?

FIGURE 1 Can a glass really shatter from someone's voice?

PRACTICALS

SUGGESTED PRACTICAL	**15.1** Investigating fundamental and harmonic wavelengths in pipes
SUGGESTED PRACTICAL	**15.2** Speed of sound in air using a closed-end pipe over water

15.1

Properties of sound waves

KEY IDEAS

In this section, you will learn about:

+ propagation of sound waves
+ the speed of sound.

Propagation of sound waves

longitudinal waves
waves where the direction of oscillation of particles is parallel to the direction of energy transfer or wave movement

medium
an elastic substance such as air or water that allows for the transfer of energy in the form of a mechanical wave

Sound waves are **longitudinal waves** producing compressions and rarefactions of the air particles in the direction the wave propagates. A **medium** is required in order to transmit sound (energy) waves and it is the collision of the material medium's particles that carries the energy. Without a medium such as air, no sound can propagate and so sound waves do not travel in a vacuum. Space is the closest approximation to a perfect vacuum – which is why space stations have to communicate via radio waves, not sound waves. Radio waves are electromagnetic waves that do not require a medium for their propagation.

CHALLENGE 15.1A

Underwater sounds

If you put your head under water while having a bath, you can hear sounds from all over the house that you wouldn't normally hear. Why is this?

The speed of sound

The more rigid the particles in a medium, the faster the sound will travel through it. This is shown in Table 1.

FIGURE 1 Sound waves can be heard from all around your house if you put your head under water while having a bath.

TABLE 1 The speed of sound in various mediums

Medium	v (m s^{-1})
Gases at 0°C	
Air	331
Carbon dioxide	259
Oxygen	316
Helium	965
Hydrogen	1290
Liquids at 20°C	
Ethanol	1160
Mercury	1450
Water, fresh	1480
Sea water	1540
Human tissue	1540
Solids (longitudinal or bulk)	
Vulcanized rubber	54
Polyethylene	920
Marble	3810
Glass, Pyrex	5640
Lead	1960
Aluminium	5120
Steel	5960

SUGGESTED PRACTICAL

15.1 Investigating fundamental and harmonic wavelengths in pipes
Go to your obook assess »

In air, particles are loosely connected, and the speed of sound is approximately 343 m s^{-1} at 20°C. The speed of sound varies with the atmospheric conditions such as temperature, humidity and air movement. As air temperature rises, the speed of sound increases by about 0.6 m s^{-1} for each degree. At 0°C, sound travels at 331 m s^{-1}, whereas at 20°C it travels at 331 + 20 × 0.6 = 343 m s^{-1}. This relationship can be used for any problem or laboratory work.

As an orchestra warms up, the pitch of wind instruments becomes higher because the speed of sound in air increases and affects the frequency of the **standing waves** inside the instruments. On the other hand, string instruments go lower in pitch because the friction of the fingers rubbing over the strings heats them up and causes them to lengthen.

In gases other than air, the speed of sound is different. You may have seen people take a lung-full of helium gas from party balloons and when they speak they sound like Donald Duck. The speed of sound in helium is about 965 m s^{-1}, which causes the resonant frequency of the throat and mouth cavity to rise.

The speed of sound is nearly independent of frequency, certainly in the audible range of 20–20 000 Hz. If this were not the case, listening to an outdoor concert would be terrible – you'd hear the high frequency sounds before the bass sounds and it would all sound out of tune.

CHALLENGE 15.1B

Candle in the wind

Put a lit candle in a room and open a door quickly. How long will the breeze take to get to the candle? Measure the distance and the time. Do you think the breeze would travel at the speed of sound in air?

CHALLENGE 15.1C

Helium in an orchestra

In *The Song of the White Horse* by David Belford, the lead soprano is required to breathe in helium to reach the extremely high top note. If some of the helium was released into the middle of the accompanying orchestra, what would happen to the pitch of the wind, brass, strings and percussion instruments?

standing waves
those with stationary vibration patterns formed due to the superposition of waves with particular frequencies

As sound is a wave, the properties common to all waves apply to sound. Sound waves can be reflected, refracted, diffracted and can interfere. The wave equation $v = f\lambda$ used for water waves applies to sound waves too.

FIGURE 2 The pitch of instruments in an orchestra changes when atmospheric conditions such as temperature and humidity change.

WORKED EXAMPLE 15.1

Calculate the wavelength of the musical note middle-C, which has a frequency of 261.6 Hz on a day when the temperature is 25°C.

SOLUTION

The wave equation is needed to calculate wavelength from frequency: $v = f\lambda$.

However, we also need the speed of sound in air at 25°C:

$$\begin{aligned} v \text{ (sound at 25°C)} &= 331 + 0.6T \\ &= 331 + 0.6 \times 25 \\ &= 331 + 15 \\ &= 346 \text{ m s}^{-1} \end{aligned}$$

Use the wave equation to calculate wavelength:

$$\begin{aligned} v &= f\lambda \\ 346 &= 261.6 \times \lambda \\ \lambda &= \frac{346}{261.6} \\ &= 1.3 \text{ m} \end{aligned}$$

CHECK YOUR LEARNING 15.1

Use 340 m s^{-1} for the speed of sound unless otherwise informed.

Describe and explain

1 **Explain** whether sound is a longitudinal or a transverse wave.

2 **Explain** how sound propagates in air.

3 **Describe** how the speed of sound in air varies with temperature.

4 **Explain** why sound travels faster in water than in air.

5 a **Calculate** the speed of a sound wave that has a frequency of 800 Hz and a wavelength of 42 cm.

b Is this sound in the audible range of hearing (20–20 000 Hz)? **Explain** your answer.

Apply, analyse and interpret

6 A student makes a noise in the back of the classroom with a frequency of 1000 Hz. **Determine** how long it will take the noise to reach the teacher in the front of the room 3.0 m from the student. What will the wavelength be for this sound?

7 When watching the fireworks at the local show, you observe that you see the flashes from the exploding fireworks in the sky 0.50 s before you hear them. Assuming light travels almost instantaneously, **determine** how far away from you the fireworks are exploding.

8 A person standing on an observation platform in the mountains shouts and then hears the echo off a cliff 1.5 s later. **Determine** how far the cliff is from the platform. Hint: echoes are reflections of the source sound back to where they originated.

Investigate, evaluate and communicate

9 Students sitting in the stands at an athletic competition 200 m from the starting line see the smoke from the starting pistol 0.6 s before hearing the sound of the gun. **Assess** how you could determine the air temperature from this information and make the calculation.

OI

Check your obook assess for these additional resources and more:

» Student book questions
Check your learning 15.1

» Suggested practical
15.1 Investigating fundamental and harmonic wavelengths in pipes

» Challenge
15.1A Underwater sounds

» Video
Interference of sound

15.2 Standing waves in strings and pipes

KEY IDEAS

In this section, you will learn about:

+ standing wave formation in strings and pipes.

Strings

mode
different standing wave patterns formed in strings and air columns

fundamental frequency
the lowest natural frequency produced by an object or musical instrument

harmonic
an integer (whole number) multiple of the fundamental frequency

When a guitar string is plucked, the string vibrates back and forth – often so fast that you cannot see it moving. A standing wave has formed between the ends of the string. The pulse you create by plucking the string travels along the string where it reflects off the end and comes back along the string to interfere with the next pulse coming down. Because the incoming and reflected waves have the same frequency, speed and amplitude, a standing wave is created.

A number of different standing wave patterns can form in a string. Recall from Chapter 14 that nodes are formed at the fixed ends. Figure 1 shows the simplest standing wave pattern established in a guitar string. This is the first way a string can vibrate, so we say it has a **mode** of vibration of $n = 1$ and is called the **fundamental frequency** or first **harmonic**.

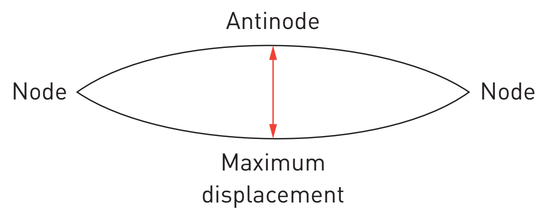


FIGURE 1 The length of the string is equal to $\frac{1}{2}\lambda$. This diagram is the first pattern we obtain, so it is called the fundamental frequency or first harmonic.

TABLE 1 Vibrating patterns (modes) for a string

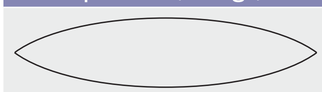
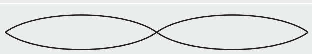
Standing wave pattern (strings)	L	λ	$f = \frac{v}{\lambda}$	f	Name	n
 A	$\frac{1\lambda}{2}$	$\lambda_1 = 2L$	$f_1 = \frac{v}{2L}$	f_1	Fundamental frequency or first harmonic	1
 B	$\frac{2\lambda}{2} = \lambda$	$\lambda_2 = L$	$f_2 = \frac{2v}{2L}$	$f_2 = 2f_1$	Second harmonic	2
 C	$\frac{3\lambda}{2} = 1\frac{1}{2}\lambda$	$\lambda_3 = \frac{2L}{3}$	$f_3 = \frac{3v}{2L}$	$f_3 = 3f_1$	Third harmonic	3

Table 1 shows the first three modes of vibration for a string.

- For the first harmonic (fundamental frequency, $n = 1$), the length of string is $\frac{1}{2}\lambda$ (which can also be written as $\frac{1\lambda}{2}$).
- For the second mode of vibration ($n = 2$), the length of the string is equal to 1λ. When you calculate its frequency using the wave equation, you find its frequency is twice the fundamental frequency. Because it is twice the fundamental frequency, it is called the second harmonic.
- For the third mode of vibration ($n = 3$), the length is equal to $1\frac{1}{2}\lambda$. Its frequency is three times the fundamental frequency, so it is called the third harmonic.

Formula for strings

A pattern emerges that relates the wavelength of the standing wave to the length of the string. The formula for strings is:

$$L = n\frac{\lambda}{2}$$

where L = length of string, n = the mode of vibration and λ = wavelength of the wave in the medium (string).

In Table 1, the frequency for each mode of vibration has also been calculated.

- For the first harmonic, the length $L = \frac{\lambda_1}{2}$. This can be rearranged to give $\lambda_1 = 2L$. The wave equation, $v = f\lambda$, can be rearranged to $f = \frac{v}{\lambda}$ and we can substitute $2L$ for the λ to give $f_1 = \frac{v}{2L}$. Note that the velocity v is the speed of the wave in the string and not in the surrounding air.
- For the second harmonic, $\lambda_2 = L$ and we can substitute this into the wave equation $f = \frac{v}{\lambda}$ to get $f_2 = \frac{v}{L}$. If we write this as $f_2 = \frac{2v}{2L}$, we can see a pattern emerging. The value $f_2 = \frac{2v}{2L}$ for the second harmonic is twice $f_1 = \frac{v}{2L}$ of the first harmonic.
- Then we can go on to the third harmonic and so on. Note that strings produce all harmonics (first, second, third, fourth, etc.)

Alternative formula for strings

From the calculations in Table 1 we have developed an alternative formula for strings:

$$f_n = \frac{nv}{2L}$$

which gives the frequency of the nth harmonic. But note that:

$$f_n = nf_1$$

which says the frequency of the nth harmonic is n times the frequency of the first harmonic.

In both these formulas, f = frequency of the sound, n = the mode of vibration, v = velocity of the wave in the medium (the string) and L = length of the string. Note that v is the velocity of the wave in the string itself, not of the sound it makes in air.

WORKED EXAMPLE 15.2A

A guitar string is 85.0 cm long and plucked in the centre to produce the fundamental frequency (first harmonic). The speed of the wave in the string is 420 m s^{-1}.

a Calculate the frequency of the vibration.

b What is the frequency of third harmonic?

SOLUTION

a $L = 0.850$ m, $v = 425$ m s^{-1}, $f = ?$

For the first harmonic in a string, $n = 1$.

Use the formula for strings:

$$L = \frac{n\lambda}{2}$$
$$= \frac{1\lambda}{2}$$
$$\lambda = 2L$$
$$= 2 \times 0.850 = 1.70 \text{ m}$$

Use the wave equation:

$v = f\lambda$ (where v is the velocity of the wave in the string)

$$f = \frac{v}{\lambda}$$

$$= \frac{420}{1.70} = 247 \text{ Hz}$$

b For the third harmonic, $n = 3$.

$$f_n = nf_1$$

$$= 3 \times f_1$$

$$= 3 \times 247 = 741 \text{ Hz}$$

Wind instruments

Wind instruments, such as the flute, produce standing waves but in an air column. As with stringed instruments, the air column can vibrate in a number of ways. The way it vibrates also depends on the nature of the instrument – whether it is closed-ended or open-ended.

Closed-end pipes

The most common example of closed-end pipes is the clarinet family of instruments. Standing waves can be produced by taking a piece of plastic drain pipe and sealing one end with a plastic cap. Place a sound generator at the open end. If the frequency is increased suddenly, it will get very loud at one particular frequency.

For example, if a 1.0 m closed-end pipe is used, when the frequency gets to 80 Hz the air in the pipe will resonate loudly. This is the first standing wave. If the frequency is continuously increased, the sound will go soft again. Then, at approximately 240 Hz, another loud point will be reached, and then it will go soft and then loud again at 400 Hz, and so on.

The air molecules in the pipe can have big movements (displacements) at the open end, but down at the closed end they can hardly move.

Figure 2 shows air movement in a closed-end pipe. The red dots represent several air particles in the pipe. The air particle at the open end (red dot 1) is free to move back and forth, as shown by the black horizontal arrow. The length of this arrow can be shown by redrawing it in the up and down direction (the vertical blue arrow). This shows the maximum displacement of the particles at every point along the tube. The first point is called the antinode, as there is maximum air movement (displacement).

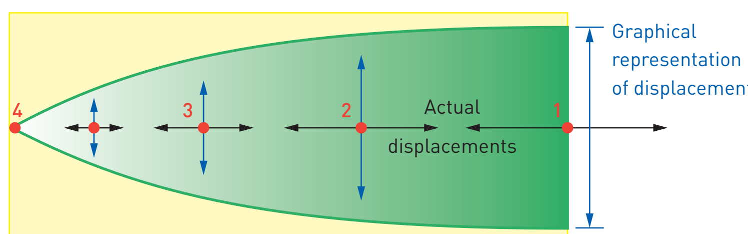


FIGURE 2 Air movement in a closed-end pipe

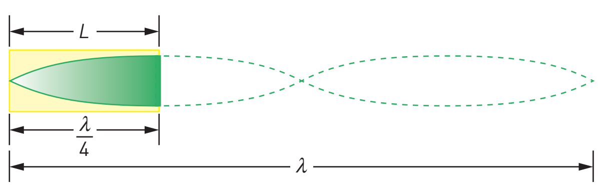


FIGURE 3 The standing wave has one-quarter of the wavelength that can resonate in the tube.

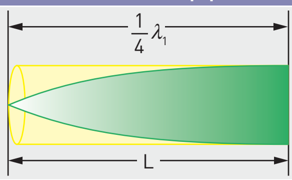
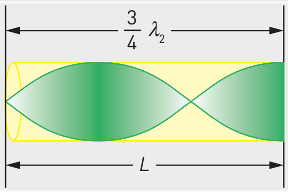
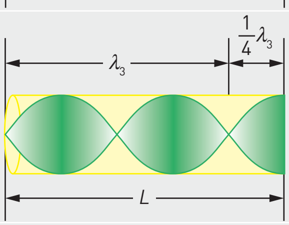
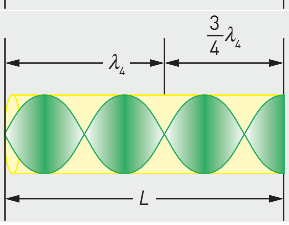
Along the pipe to the left, the amount of movement gets less. This is shown by the second air particle (red dot 2) and the length of the horizontal and vertical arrows. Further to the left it gets smaller, and then at the closed end (red dot 4) the particle can't move so the arrow length is zero. This is called the node.

In this situation, the standing wave has one-quarter of the wavelength that can resonate in the tube (Figure 3).

The length of the tube L is just one-quarter of the wavelength, or $L = \frac{1}{4}\lambda$. Continuing this process reveals a whole series of shorter wavelength and higher-frequency sounds that resonate in the tube. The lowest resonant frequency is called the fundamental frequency (or first harmonic). All resonant frequencies are integral (whole number) multiples of the fundamental, and they are collectively called harmonics. The fundamental frequency is the first harmonic, next is the third harmonic, then the fifth harmonic and so on.

Table 2 shows the fundamental frequency and the next three harmonics in a closed-end pipe.

TABLE 2 Harmonics for a closed-end pipe

Standing wave pattern (closed-end pipe)	L	λ	$f = \frac{v}{\lambda}$	f	Name	n
	$\frac{1\lambda_1}{4}$	$\lambda_1 = 4L$	$f_1 = \frac{v}{4L}$	f_1	Fundamental frequency – First harmonic (n = 1)	1
	$\frac{3\lambda_2}{4}$	$\lambda_2 = \frac{4L}{3}$	$f_3 = \frac{3v}{4L}$	$f_3 = 3f_1$	Third harmonic (its frequency is 3 times the fundamental frequency)	2
	$\frac{5\lambda_3}{4}$	$\lambda_3 = \frac{4L}{5}$	$f_5 = \frac{5v}{4L}$	$f_5 = 5f_1$	Fifth harmonic	3
	$\frac{7\lambda_4}{4}$	$\lambda_4 = \frac{4L}{7}$	$f_7 = \frac{7v}{4L}$	$f_7 = 7f_1$	Seventh harmonic	4

Formula for closed-end pipes

In the table, we can see a pattern for wavelength:

$$L = (2n - 1)\frac{\lambda_n}{4}$$

where L = length of the closed-end pipe, n = mode of vibration (the counting numbers 1, 2, 3, 4), and λ_n = wavelength of the standing wave in the pipe vibrating in its nth mode of vibration.

Alternative formula for closed-end pipes

We can rearrange the formula to $\lambda_n = \frac{4L}{(2n-1)}$ and substitute into the wave equation $v = f\lambda$ to produce alternative formulas:

$$f_n = \frac{v}{\lambda_n}$$

$$f_n = \frac{(2n-1)v}{4L}$$

$$f_n = (2n-1)f_1$$

SUGGESTED PRACTICAL

15.2 Speed of sound in air using a closed-end pipe over water
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WORKED EXAMPLE 15.2B

The speed of sound waves in air at a particular temperature is 340 m s^{-1}. Determine the fundamental frequency (first harmonic) of a closed-end air column that has a length of 67.5 cm.

SOLUTION

For first harmonic:

$\lambda = 4L$

$= 4 \times 0.675$

$= 2.70$ m

Using the wave equation:

$v = f\lambda$

$f = \frac{v}{\lambda}$

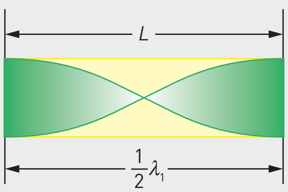
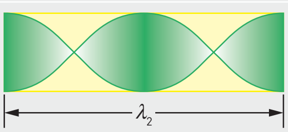
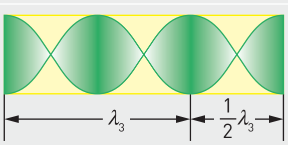
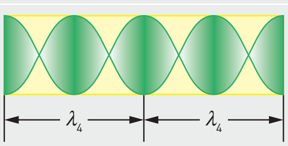
$= \frac{340}{2.70}$

$= 126$ Hz

Open-end pipes

Another type of pipe is one that is open at both ends. Examples are flutes and oboes. The resonances of pipes open at both ends can be analysed in a very similar way to those for pipes closed at one end. The air columns in pipes open at both ends have maximum air displacements at both ends, as illustrated in Table 3, with a standing wave form as shown.

TABLE 3 Harmonics for a open-end pipe

Standing wave pattern	L	λ	$f = \frac{v}{\lambda}$	f	Name	n
	$\frac{\lambda_1}{2}$	$\lambda_1 = 2L$	$f_1 = \frac{v}{2L}$	f_1	Fundamental frequency or first harmonic	1
	λ_2 or $\frac{2\lambda_2}{2}$	$\lambda_2 = L$	$f_2 = \frac{2v}{2L}$	$f_2 = 2f_1$	Second harmonic (its frequency is 2 times the fundamental frequency)	2
	$\frac{3\lambda_3}{2}$	$\lambda_3 = \frac{2L}{3}$	$f_3 = \frac{3v}{2L}$	$f_3 = 3f_1$	Third harmonic	3
	$\frac{4\lambda_4}{2}$	$\lambda_4 = \frac{2L}{4}$	$f_4 = \frac{4v}{2L}$	$f_4 = 4f_1$	Fourth harmonic	4

Formula for open-end pipes

As with the closed-end pipe, the resonances in open-end pipes have distinct frequencies. The formula that relates length of pipe, wavelength and frequency for the various modes of vibration is:

$$L = \frac{n\lambda_n}{2}$$

where L = length of the open-end pipe, n = mode of vibration (1, 2, 3, 4 …), and λ_n = the wavelength of the standing wave for the nth mode of vibration. Note that this is the same formula for strings.

Alternative formulas for open-end pipes

We can rearrange the formula to $\lambda_n = \frac{2L}{n}$ and substitute into the wave equation $v = f\lambda$ to produce alternative formulas:

$$f_n = \frac{v}{\lambda_n}$$

$$f_n = \frac{nv}{2L}$$

$$f_n = nf_1$$

WORKED EXAMPLE 15.2C

The speed of sound waves in air at 25°C is 346 m s^{-1}. In an experiment, students want to make an open-end pipe that has a fundamental frequency for the musical note C_3, which is 130.8 Hz. Determine the length of such a pipe.

SOLUTION

Calculate the wavelength using the wave equation:

$$v = f\lambda$$

$$\lambda = \frac{v}{f}$$

$$= \frac{346}{130.8}$$

$$= 2.65 \text{ m}$$

Calculate the length using the length formula for open-end pipes:

$$L = \frac{n\lambda_n}{2}$$

For the first harmonic, $n = 1$

$$L = \frac{1 \times \lambda_1}{2}$$

$$= \frac{1 \times 2.65}{2}$$

$$= 1.33 \text{ m}$$

The pipe should be 1.33 m long.

Summary of relationships

TABLE 4 Formulas for open-end and closed-end pipes

String and open-end pipe	$L = \frac{n\lambda_n}{2}$	$f_n = \frac{nv}{2L}$	$f_n = nf_1$
Closed-end pipe	$L = (2n-1)\frac{\lambda_n}{4}$	$f_n = \frac{(2n-1)v}{4L}$	$f_n = (2n-1)f_1$

CHALLENGE 15.2

Singing wineglasses

Dip your finger in some water and run it around the rim of a wine glass (Figure 4). A loud sound is produced. Why doesn't this sound work if your finger is a bit oily?

FIGURE 4 Dipping your finger and running it around the rim of a wine glass can cause it to 'sing'.

CHECK YOUR LEARNING 15.2

Describe and explain

1 **Explain** the meaning of the symbols in the string formula $L = \frac{n\lambda_n}{2}$ and give an example of its use.

2 **Recall** whether strings produce all harmonics. Give a reasoned explanation for your answer.

3 Can you have more than one wavelength at a time produced on a particular string? **Explain** using a first and second harmonic as an example.

4 **Explain** the meaning of the symbols in the open-end pipe formula $f_n = \frac{nv}{2L}$ and give an example of its use.

5 **Calculate** the length of a guitar string that produces a fundamental frequency (first harmonic) of 261 Hz. The speed of waves in a particular guitar string is measured as 395 m s^{-1}.

6 The third harmonic of a violin string has a frequency of 1200 Hz. **Calculate** its fundamental frequency.

7 A guitar string is 0.60 m long and the speed of the waves on it is 200 m s^{-1}. **Calculate** its fundamental frequency.

8 Figure 5 shows the seventh harmonic in a closed-end pipe. **Sketch** a diagram showing the waveform for the ninth harmonic.

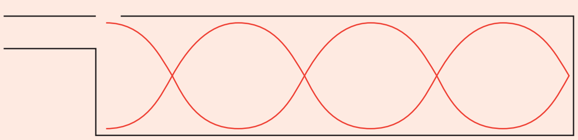


FIGURE 5 The seventh harmonic in a closed-end pipe

Apply, analyse and interpret

9 A student blows across the top of a test tube that has a 17.2 cm air column closed at one end. The speed of sound in the air in test tube is 340 m s^{-1}. **Calculate** the frequency of the first harmonic played by this instrument.

10 A string that has a length of 2.5 m resonates in five loops (Figure 6) with a frequency of 2.00 Hz.

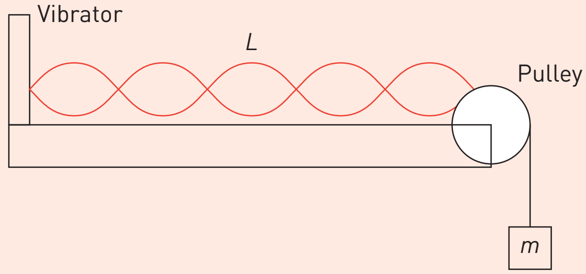


FIGURE 6 The string resonates in five loops.

a **Determine** the wavelength.

b **Calculate** the wave speed.

c **Deduce** which harmonic it is.

11 A closed-end pipe produces both the third and fifth harmonics with frequencies of 1100 Hz and 1833 Hz respectively.

a **Calculate** the frequency of the first harmonic.

b If the air temperature is 20°C, **determine** the length of the pipe.

12 A student blows across the mouth of a closed-end plastic pipe 0.30 m long. **Determine** the fundamental frequency and the frequency of the fifth harmonic. Assume the speed of sound in air is 340 m s^{-1}.

13 a **Sketch** the standing wave patterns set up in an open-end pipe whose length is 20 cm and where the pipe's length equals:

i $1\frac{1}{2}\lambda$ ii 3λ iii $\frac{1}{2}\lambda$

b **Determine** the resultant frequencies emitted by the pipe in the above situations.

Investigate, evaluate and communicate

14 To measure the speed of sound in air, students set up a source of sound at one end of an open cardboard tube. This cardboard tube had another open tube fitted inside it that could be adjusted to change the length. Students set the frequency generator at 600.0 Hz and located the first resonance at a length of 9.8 cm (0.098 m). They repeated this two more times. The students then lengthened the tube until the second resonance was located. They repeated this procedure for the first five resonances, testing triplicates for each one. The air temperature was 24.4°C. Their data is recorded in Table 5.

TABLE 5

Harmonic (mode)	Length of pipe, *L* (m)		
n	Test 1	Test 2	Test 3
1	0.098	0.107	0.106
2	0.379	0.411	0.345
3	0.646	0.718	0.688
4	0.955	1.026	0.916
5	1.183	1.305	1.242

a **Calculate** the mean (average) length of the pipe for each resonance, and absolute uncertainty (δ) of the mean for each.

b **Sketch** a graph of length (L) on the vertical axis vs harmonic number (mode, n) on the horizontal axis. Add error bars for the absolute uncertainty. Identify the trend by determining the equation for the line and calculating the R^2 value.

c **Derive** the wavelength of the sound by multiplying the slope by 2. Note that the slope (gradient) should be equal to $\frac{\lambda}{2}$.

d **Calculate** the (observed) velocity of the sound using $v = f\lambda$.

e Draw maximum and minimum trendlines and **calculate** the gradients. Use the gradients to calculate the maximum and minimum values of the speed of sound. Express this as the uncertainty in the experimental value.

f **Calculate** the accepted velocity using $v = 331.5 + 0.6T$ where T = temperature in degrees Celsius.

g **Calculate** the absolute and percentage errors.

h **Deduce** why it was stated that the slope is equal to $\frac{\lambda}{2}$.

i **Comment** on the uncertainty and accuracy of the students' measurements.

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» Suggested practical
15.2 Speed of sound in air using a closed-end pipe over water

» Challenge
15.2 Singing wineglasses

» Video
Standing waves

15.3 Resonance and natural frequency

KEY IDEAS

In this section, you will learn about:

- natural frequency
- resonance.

Forced vibrations

When a tuning fork is struck on the bench, it vibrates at its natural fundamental frequency (as well as emitting a few other, but less intense, harmonics). This fundamental frequency depends on the length, thickness and composition of the tuning fork. The intensity of the sound produced can be increased by placing the end of the tuning fork on a table top. The table top is forced to vibrate at the same frequency as the fork, thus intensifying the sound produced.

forced vibration the tendency of one object to force another adjoining or interconnected object into vibrational motion

This **forced vibration** also occurs for a guitar string. When a guitar string is held between two clamps and plucked, it does not produce a very intense sound. However, when the string is attached across the bridge of a guitar and plucked, the sound is more intense because the wood of the guitar (the 'soundboard') is forced to vibrate in response to the vibrating string.

Resonance

resonance when a vibrating object or external force causes another system to oscillate with greater energy at a particular frequency

When a tuning fork is struck, it vibrates at its natural frequency. If there is another tuning fork of the same frequency close by, it too will begin to vibrate. We say that the first tuning fork has caused **resonance** in the second one. Resonance is the effect that occurs when a body is caused or forced to vibrate at its natural frequency. With resonance, energy is transferred efficiently from one object to another. If resonance is not occurring, the energy is dissipated (spread out) as heat and random vibrations of nearby matter. Resonance occurs in many different systems including strings, air columns and atoms.

Resonance on a swing

natural frequency the frequency at which an object will resonate when made to vibrate by an imposed frequency or force

Imagine a child on a swing (Figure 1). Together, the child and swing are like a pendulum. The length of the swing is fixed, so the swing oscillates (swings back and forth) at a set frequency. You can't do a lot to change it as the swing has a **natural frequency**. Natural frequency is the frequency at which a system oscillates when not subjected to a continuous or repeated external force. Natural frequency is also called the resonant frequency.

To transfer energy to the swing it must be pushed in time with the swinging movement – it must be pushed with the same frequency as the natural frequency. When this happens, the swing will get higher and higher. Of course, the pushing frequency must be in phase too. The swing must be pushed at exactly the right time or it won't go higher. The push must be applied at the end points of the cycle. A fraction of a second early or late and the swing will slow down. The external force will create resonance if it is applied with the natural frequency of the system and in phase.

At resonance, energy is transferred rapidly and efficiently to the oscillating system, and the amplitude of its oscillations grows (the swing gets higher and higher).

FIGURE 1 A child being pushed on a swing is an example of resonance. Push at the right time and the energy will be transferred efficiently to the vibrating system and the amplitude will increase – it will resonate. Push at the wrong time and energy will be dissipated and the amplitude will decrease – it won't resonate.

Resonance in pipes

When you blow across the top of a test tube, a loud sound can be heard. If the test tubes are filled to different levels with water, you can obtain sounds of different frequencies that depend on the length of the air column above the water. The test tube is acting like a pipe closed at one end. You may have made straw clarinets in your Year 9 science class. Straw clarinets are different lengths of plastic drinking straws that acted as open-end pipes and produced notes of different frequencies depending on the length. They were cut into a V-shape at one end so they could vibrate.

We can use the idea of resonance to measure the speed of sound in air. By sounding a tuning fork over the open end of a plastic pipe whose length can be changed by raising and lowering it in water, we can achieve resonance. At some particular length of the pipe above water, you will find a point where the pipe begins to hum loudly. We can say the pipe is resonating at that frequency (of the tuning fork) and a standing wave is produced. When it is not resonating, the energy of the vibrations goes into the air and dissipates in all directions. At resonance, the energy is largely transferred to the air in the pipe to create the standing wave and the hum. At resonance, energy is being transferred efficiently.

Other examples of resonance

Examples of resonating musical instruments include wind instruments that use resonance in air columns to amplify tones made by lips or vibrating reeds. Other instruments also use air resonance in clever ways to amplify sound.

A violin and a guitar both have sounding boxes but with different shapes, resulting in different resonant frequencies. The vibrating string creates a sound that resonates in the sounding box, greatly amplifying the sound and creating overtones that give the instrument its characteristic 'flavour'. The more complex the shape of the sounding box, the greater its ability to resonate over a wide range of frequencies.

Resonance vibration is why soldiers avoid marching in step when crossing older bridges as they might cause the bridge to resonate and possibly collapse. A similar problem occurred with the Millennium Bridge in London, but this situation was horizontal motion instead of vertical. When 2000 people walked on the bridge on opening day in 2000, sideways motion of 1.3 Hz caused the bridge to lurch to one side. Pedestrians had to adjust their steps to keep from falling over, and they all did this at exactly the same time. The bridge was subsequently closed for two years while engineers tried to rid it of resonance problems.

FIGURE 2 Millennium Bridge, London

CHECK YOUR LEARNING 15.3

Describe and explain

1 **Describe** what a 'natural frequency of vibration' means.

2 a **Explain** what resonance is and how it is produced.

b **Explain** why some older cars and buses start to vibrate when their engines reach certain 'revs' (revolutions per minute).

3 **Describe** the relationship between energy transfer and the resonance condition.

4 Students held a 220 Hz tuning fork over a pipe closed at one end (in water). They found two lengths that gave resonance. **Sketch** diagrams to suggest how this can be.

Apply, analyse and interpret

5 **Recall** a practical example where resonance is a problem and explain how it could be reduced.

6 A car travelling over a corrugated 'washboard' road vibrates up and down very dramatically when the speed is 10 km h^{-1}. **Interpret** this scenario and explain how the driver could prevent this happening.

Investigate, evaluate and communicate

7 A child is being pushed on a swing that is oscillating at its natural resonant frequency of 1 complete swing every 4 seconds. The child stands up. Predict whether the resonant frequency will now be higher, lower or the same. **Justify** your response.

8 A claim was made that resonance in the Millennium Bridge was similar to soldiers marching in lockstep, but with motion horizontal instead of vertical. **Evaluate** what is meant by 'horizontal instead of vertical'.

Check your obook assess for these additional resources and more:

» Student book questions
Check your learning 15.3

» Increase your knowledge
Forced vibrations
Beats

» Video
Resonance in a harmony bowl

» Video worksheet
Resonance in a harmony bowl

SCIENCE AS A HUMAN ENDEAVOUR

15.4 Noise pollution and acoustic design

KEY IDEAS

In this section, you will learn about:

+ intensity of sound.

Noise from roadways is a major source of noise pollution. Before it can be applied to the laws of physics, noise must be quantified so that it can be measured objectively.

Measuring sound intensity

Sound intensity is measured in the unit decibel (dB). The formula is:

$$\beta = 10\log_{10}\left(\frac{I}{I_0}\right)$$

where I_0 is the intensity of a measures sound in watts per square metre (W m^{-2}) and where I_0 is the reference level, taken as the least audible sound (10^{-12} W m^{-2}), and β is the relative intensity level in dB.

In industry, sound intensity is often referred to as the **sound pressure level (SPL)**. Ordinary conversation has an SPL of about 60 dB, and a noisy restaurant is 80 dB.

A sound level meter has a display that gives a reading of the SPL in dB. The meter uses a weighted average of the SPL values over a range of frequencies in the audible region to approximate the human ear – less weighting for the low frequencies and more weighing for the mid-range frequencies. This is called a dBa measurement.

Measuring road noise

FIGURE 1 A noise monitoring device placed near the most exposed facade of a residential building

Placing a sound level meter in the correct location is critical for measuring SPLs beside a roadway to determine if nearby homeowners are being subjected to excessive noise. The sound level meter must be positioned on a stand exactly 1 m in front of the nearest window facing the roadway. This measures the 'façade noise' – noise received at the front of the building. Reflection from windows adds about 3 dB to the SPL, and this value is used by engineers in estimating noise. Without the reflection, the value is called free field noise.

Measuring road noise once per day would not give an accurate measure of the noise. A truck passing at the very instant the measurement was taken would produce an unfair result. To give a fair measurement of road noise, two types of measurements are taken:

- LA10 (1 hour) measurement – The noise level is measured continuously over a 1-hour period, and the value of the noise level exceeded (dB) for $\frac{1}{10}$ of the time (6 minutes) is noted. An LA10 (1 hour) result of 70 dB means the noise was over 70 dB for exactly 6 minutes.
- LA10 (18 hour) – The average of 12 LA10 (1 hour) readings taken each hour between 6 am and midnight.

Different Australian states have different standards, but in Queensland it is usual to specify that the LA10 (18 hour) has to be less than 68 dB in general, and less than 63 dB for residential, educational, community and health buildings.

Reducing road noise

It is not possible to eliminate excess noise completely, but it can be managed to keep it within reasonable limits. There are four ways of controlling noise from traffic:

1. **Limit generation of noise** – Most road noise is from tyres on the road, and the only way to reduce this is by using low-noise pavement.
2. **Reduce transmission of noise** – Barriers can be constructed to stop sound travelling. Noise walls or noise reduction panels can be effective if they are the right height, are made of the right material, and have no gaps.
3. **Insulate occupants from noise** – There are several ways of stopping sound getting into a house, which all involve some form of insulation or sound proofing. Double-glazed windows have an air layer trapped between the layers of glass, which acts as a poor conductor of sound.
4. **Regulate traffic to minimise impact** – There are already many regulations about traffic noise control such as ensuring mufflers are in working order, limiting use of air brakes by trucks, and reducing road speeds in residential areas.

Issues with using noise walls

In theory, it would seem that a thick-enough fence or barrier could cut out all the noise. This is partly true. A thick wall will reduce noise, but unless it is high enough it won't stop the noise entirely. Sound is difficult to stop with a barrier due to the property of sound waves known as diffraction. Diffraction is the bending of waves as they pass a barrier (see Chapter 14). The lower the frequency, the more the waves are bent. For roads, the peak traffic noise is between 500 and 1500 Hz, which is quite low in the audible range of 20–20 000 Hz. A lot of diffraction of sound waves takes place at low frequencies (Figure 2). Ultimately, no matter how good the barrier is for transmitted waves, diffracted waves will make it to the receiver unless the barrier is high enough.

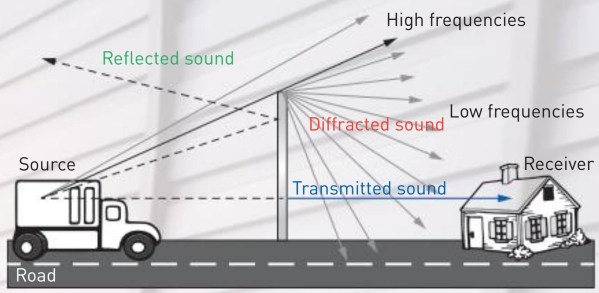

FIGURE 2 Sound propagation paths in the presence of a noise barrier. Note that the low frequencies are diffracted down behind the fence. The transmitted sound is reduced by the barrier and could be eliminated entirely with a good barrier.

CHECK YOUR LEARNING 15.4

Describe and explain

1. **Explain** the meaning of 'decibel'.
2. **Explain** why sound barriers are not as effective for low frequency sounds.
3. **Explain** in what way the diffraction of water waves (as described in Chapter 14) is similar to the way sound passes over a barrier.

Investigate, evaluate and communicate

4. **Evaluate** if it is true to say, 'If the loudness of a sound is doubled, the decibel level doubles'?

Check your obook assess for these additional resources and more:

- » Student book questions
  Check your learning 15.4
- » Increase your knowledge
  Measuring noise pollution
- » Weblink
  Effects of noise pollution
- » Weblink
  Noise control and your home

CHAPTER 15

Review

Summary

15.1
- Sound is a form of energy produced by vibrating objects.
- Sound travels by means of longitudinal mechanical waves that require a medium for propagation.
- The loudness of a sound refers to the amplitude of the wave or the energy carried by the wave.
- The speed of sound in air is 331 m s^{-1} at 0°C but increases by 0.6 m s^{-1} for every degree Celsius higher than 0°C. At 25°C the speed is 346 m s^{-1}.

15.2
- The lowest frequency produced by a musical instrument is called the fundamental frequency (or first harmonic).
- Musical sounds are produced by standing waves being set up in musical instruments such as stringed instruments, open-end pipes and closed-end pipes. The frequency of sound produced depends on the standing wave patterns.
- The standing wave patterns are called 'modes' of vibration.

15.3
- Resonance is the effect that occurs when a body vibrates at its natural frequency.
- Energy is transferred efficiently in resonating systems.

Key terms

- diffraction
- forced vibration
- fundamental frequency
- harmonic
- longitudinal waves
- medium
- mode
- natural frequency
- resonance
- standing waves
- wave equation

Key formulas

Length of strings and open-end pipes	$L = n\frac{\lambda}{2}$
Length of closed-end pipe (at one end)	$L = (2n - 1)\frac{\lambda}{4}$
Wave formula	$v = f\lambda$

Revision questions

The relative difficulty of these questions is indicated by the number of stars beside each question number: * = low; ** = medium; *** = high.

Multiple-choice

1 Standing waves are produced by the superposition of two waves with:

- **A** the same amplitude, frequency and direction of propagation.
- **B** the same amplitude and frequency, and opposite propagation directions.
- **C** the same amplitude and direction of propagation, but different frequencies.
- **D** the same amplitude, different frequencies and opposite directions of propagation.

2 The fundamental frequency of a certain string is 100 Hz. Which of the following frequencies is the next harmonic?

- **A** 50 Hz
- **B** 200 Hz
- **C** 300 Hz
- **D** 400 Hz

3 The fundamental frequency of an open tube will double if:

- **A** one of the open ends is closed.
- **B** the length of the tube is doubled.
- **C** the gas in the tube is changed to one with twice the speed of sound of the original gas.
- **D** the radius of the tube is decrease to half its original value.

4 On a cold day the speed of sound in air is 320 m s^{-1}. A fundamental standing wave is produced in a tube at a frequency of 80 Hz. The next standing wave can be heard when the frequency reaches 240 Hz. Which of the following is correct?

- **A** The tube is an open-end pipe with a length of 1 m.
- **B** The tube is a closed-end pipe with a length of 1 m.
- **C** The tube is an open-end pipe with a length of 4 m.
- **D** The tube is a closed-end pipe with a length of 4 m.

5 A 4.0 m long wire with a mass of 60 g is under tension. A transverse wave is propagated on the wire. The frequency is 330 Hz, the wavelength is 0.20 m and the amplitude is 7.0 mm.
The time for a crest of the transverse wave to travel the length of the wire, in ms, is closest to:

- **A** 53
- **B** 61
- **C** 75
- **D** 82

Short answer

Describe and explain

★ 6 **Explain** the difference between a transverse wave and a longitudinal wave using labelled diagrams.

★ 7 **Define** these terms in relation to a longitudinal wave: displacement, amplitude, compression, rarefaction, equilibrium position, mechanical wave, medium and propagation.

★ 8 A classical guitar string has a 'scale' (vibrating) length of 66.0 cm. **Calculate** the wavelengths of the first, second and third harmonics.

★ 9 A student produces a note by blowing across the mouth of an open-end piece of plastic pipe 0.2 m long. **Calculate** the frequency of the third harmonic.

★ 10 A string has a length of 65 cm and when vibrating has a wavelength of 1.30 m. Is it vibrating in its fundamental mode? **Explain** your reasoning.

★ 11 The sixth string (low E) on a Fender guitar has a length of 648 mm and is tuned to a frequency of 82.1 Hz.

- **a** When vibrating in its fundamental mode, **calculate** the speed of the wave in the string.
- **b** **Calculate** the wavelength of the fundamental frequency and the second harmonic.

★★ 12 **Sketch** diagrams to show the standing waves set up in a harp string of length *L* when the length of the string corresponds to:

- **a** two wavelengths
- **b** three and a half wavelengths
- **c** four wavelengths.

Apply, analyse and interpret

(For all questions use v_{sound} = 340 m s^{-1} unless specified.)

★ **13** Figure 1 is a diagram of a standing wave.

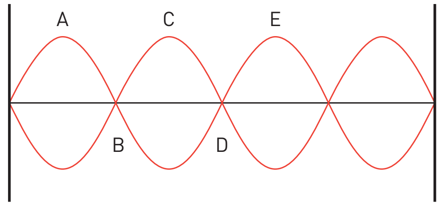

FIGURE 1 Standing wave

- **a** **Identify** the letters corresponding to nodes and antinodes.
- **b** **Determine** whether A and C, or A and E, are one wavelength apart. Explain.

★ **14** A tuning fork produces 2.4 × 10^4 compressions and rarefactions in the air particles around it in 10 s. The distance between each compression is 0.14 m.

- **a** **Calculate** the frequency of the tuning fork.
- **b** **Determine** the velocity of sound in air.

★ **15** In a thunderstorm, the lightning is seen before the thunder is heard as the velocity of light is much greater than the velocity of sound. If the thunder is heard 10 s after the lightning is seen, **determine** how far away the storm is. Assume the velocity of light is instantaneous over this distance.

★ **16** A marine survey vessel plotting the contours of the ocean floor sends an ultrasonic wave and receives an echo back 1.2 s later. **Determine** the depth of the ocean at this point. (The velocity of sound in sea water is 1400 m s^{-1}.)

★ **17** Students experimenting with musical notes set up a row of test tubes in a test tube rack and fill them with water to various levels. The students can create different notes by blowing across the top of the tubes.

- **a** If the distance between the top of the water and the top of the test tube for the first one is 8.0 cm, **determine** the fundamental frequency emitted by this tube.
- **b** **Describe** what the students will need to do to create different frequencies, and calculate the distances from the top of the tubes to the water if they wish to create fundamental frequencies of:
  - **i** half that in part (a)
  - **ii** twice that in part (a)
  - **iii** three times that in part (a).

★★ **18** Open-end and closed-end pipes can produce the same fundamental frequency.

- **a** **Calculate** the fundamental frequency produced by a closed-end pipe of length 25 cm.
- **b** **Determine** the length of an open-end pipe that would produce the same fundamental frequency.
- **c** Even though they both produce the same fundamental frequency, they would sound different. **Explain** with calculations why this occurs.

★★ **19** A pipe is open at both ends and is 0.58 m long.

- **a** **Determine** the wavelength of the sound that would produce the fundamental frequency in this pipe. (The speed of sound is 342 m s^{-1}.)
- **b** **Calculate** the frequency of the second and third harmonics.

Investigate, evaluate and communicate

★ **20** **Devise** a method for how you could demonstrate experimentally that sound waves transfer energy.

★ **21** **Decide** whether any energy is lost when waves interfere both constructively and destructively.

★★ **22** Figure 2 is a graphical representation of a standing wave in a musical instrument.

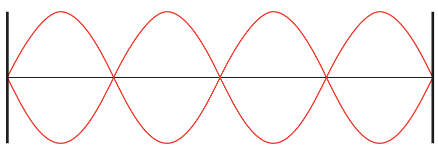

FIGURE 2 Standing wave in a musical instrument

Interpret the diagram to state whether the instrument is a string, open-end pipe or closed-end pipe. **Justify** your decision.

★★ **23** **Discuss** the possibility of open-end organ pipes producing different frequency notes on hot or cold days.

★★★ **24** An open-end tube is placed into a container of water and a vibrating tuning fork is placed over the mouth of the tube (Figure 3). As the tube is raised so that a greater length of the tube is out of the water, resonance is heard. This occurs when the distance from the top of the tube to the water level is 21 cm, and again at 59 cm.

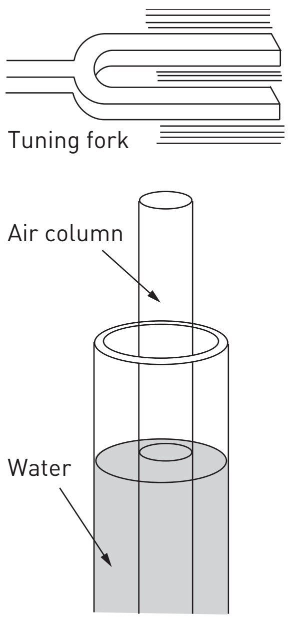

FIGURE 3 What is the frequency of the tuning fork?

Determine the frequency of the tuning fork. Hint: draw diagrams of the standing waves produced for each length and deduce what the difference in the length corresponds to.

★★★ **25** The vocal tract can be approximated as a 17.5 cm pipe closed at one end. It is made up of the mouth, pharynx and larynx, with the vocal cords making vibrations at one end.

a **Determine** the resonant frequency of the fundamental frequency and the next three harmonics.

b **Propose** a reason that men usually have lower resonant frequencies than women.

★★★ **26** Figure 4 shows a 1.0 m long vertical tube filled with water. The water is slowly let out by a tap at the bottom of the tube while a tuning fork of frequency 512.0 Hz is sounded and held over the top of the tube. (Note: the speed of sound in air for this experiment is 340.0 m s^{-1}).

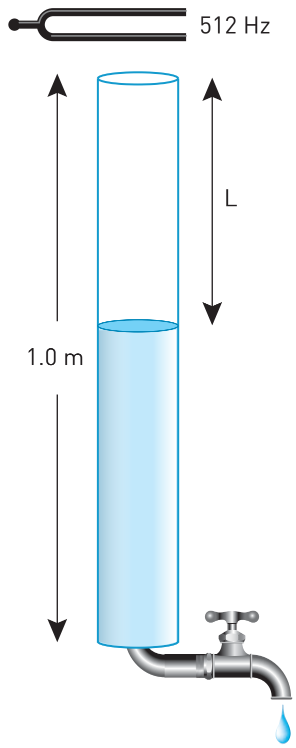

FIGURE 4 What will the observer hear in this situation?

Considering an observer is solely interested in any resonance sound coming from the tube due to the vibration of the tuning fork, **determine** and **discuss** what the observer will hear from the time the tube starts to empty until it is empty of water. Use both calculations and diagrams to support your explanation.

Check your obook assess for these additional resources and more:

» Student book questions
Chapter 15 revision questions

» Revision notes
Chapter 15

» assess quiz
Auto-correcting multiple choice quiz

» Flashcard glossary
Chapter 15

CHAPTER 16

Light

Light has played an important role in the evolution of humans. Light from the Sun has supplied the energy for plants to photosynthesise and provide food for people. A by-product of this process is the production of oxygen via photosynthesis – a necessary ingredient for sustaining life on Earth.

People have also begun to rely on solar energy. Solar energy is important for conservation of other forms of energy. Light energy can be used to heat hot water systems, produce electricity, fuel cars and provide power for households.

Most importantly, light allows humans to see. With light, humans are able to identify objects and see colours.

OBJECTIVES

→ Recall that light is not modelled as a mechanical wave, because it can travel through a vacuum.

→ Recall that a wave model of light can explain reflection, refraction, total internal reflection, dispersion, diffraction and interference.

→ Describe polarisation using a transverse wave model.

→ Use ray diagrams to demonstrate the reflection and refraction of light.

→ Solve problems involving the reflection of light on plane mirrors.

→ Define Snell's law.

→ Solve problems involving the refraction of light at the boundary between two mediums.

→ Recall that the speed of light in a vacuum is $c = 3 \times 10^8$ m s $^{-1}$.

→ Contrast the speed of light and the speed of mechanical waves.

→ Define the concept of intensity.

→ Solve problems involving the proportional relationship between intensity of light and the inverse-square of the distance from the source.

Source: *Physics 2019 v1.2 General Senior Syllabus Queensland Curriculum & Assessment Authority*

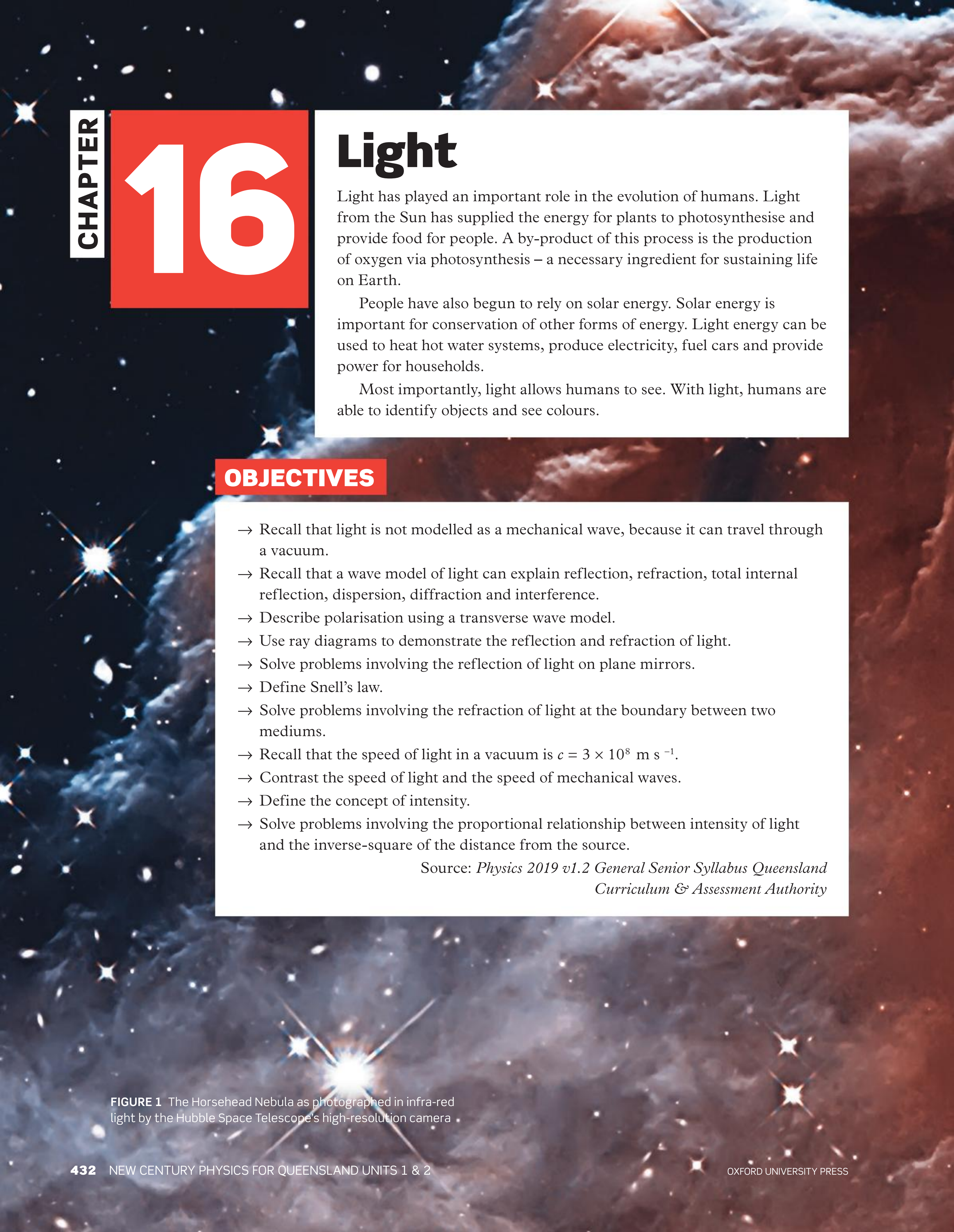

FIGURE 1 The Horsehead Nebula as photographed in infra-red light by the Hubble Space Telescope's high-resolution camera

MAKE YOU WONDER

In this chapter you will learn about concepts of wave energy to help answer questions such as:

→ If microwaves have wavelengths of 12 cm, why do they call them 'micro'?
→ If a camera lens is made of clear glass, why does it look purple?
→ Why do objects in water seem closer than they really are?
→ If you had a powerful enough microscope, could you see a single atom?
→ How can light be both a wave and a particle? Surely, it is one or the other?

PRACTICALS

MANDATORY PRACTICAL	**16.1** Refractive index of a transparent substance
SUGGESTED PRACTICAL	**16.2** Verifying the law of reflection – images in a plane mirror

16.1 The wave model of light

KEY IDEAS

In this section, you will learn about:

+ light not being modelled as a mechanical wave because it can travel through a vacuum
+ the wave and particle models of light.

electromagnetic wave
wave that requires no medium for transmission and travel at the speed of light in a vacuum; includes long wavelength radio waves through to short wavelength gamma rays (called the electromagnetic spectrum)

wave model of light
uses the characteristics of waves such as wavelength, frequency and speed to describe the behaviour of light

particle model of light
uses photons to describe the behaviour of light such as the photoelectric effect and atomic spectra

In the previous chapter we investigated the properties of mechanical waves – in particular, water and sound waves. Mechanical waves need a medium for their propagation, such as air, water and steel. The other type of wave is an **electromagnetic wave**, which does not require a medium for its propagation. Light is not modelled as a mechanical wave as it can travel through a vacuum.

Although visible light enables objects to be seen, it is just a small part of all the electromagnetic waves that exist. Radio waves, microwaves and infra-red waves are all examples of electromagnetic waves.

Models of light

There are two main models for light that provide understanding of its behaviour as it interacts with matter.

1 Wave model

The **wave model of light** was invented in the mid-1600s as a useful tool to understand how energy spreads. From the late 17th century through to the 1860s, scientists continued to refine their understanding of light and its wave-like behaviour through experimentation. The current wave model describes a travelling energy wave using quantities such as wavelength, frequency and speed. The wave model explains diffraction and interference, and how light can 'bend' around corners. The theory of diffraction can be used to explain the wing colours of Christmas beetles and to construct better microscopes.

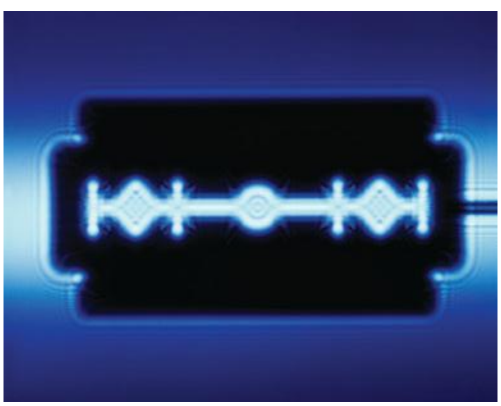

FIGURE 1 Diffraction of light through a razor blade. The diffraction of light occurs around the edges of objects and through small apertures because light bends as it passes near an object. The particle model can't explain this phenomenon because the light is not travelling in straight lines.

2 Particle model

In the mid-1600s, European philosopher Pierre Gassendi asserted (without evidence) that light was made up of 'corpuscles'. He imagined that these were infinitesimally small, perfectly elastic particles that travelled in straight lines and lit up any object they met. The **particle model of light** disappeared for 250 years, despite Newton's defence of it, as interest in the wave model grew.

In 1927, the particle model returned as the only way to explain atomic spectra and the photoelectric effect, but it couldn't explain diffraction (Figure 1), interference and polarisation.

Quantum theory

Each of the models of light can explain many of the characteristics of light, but neither can explain them all. In 1927, a unified theory called the quantum theory was developed to unify both models. The quantum theory says that light can be modelled as both a particle and

MANDATORY PRACTICAL

16.1 Refractive index of a transparent substance
Go to page 488 »

a wave, and that they are complementary rather than rival conceptions. The theory shows, in a systematic and logical way, that each model can be used in appropriate contexts.

For this chapter, we will assume that light travels through space by means of waves that can also be depicted as rays. The particle model will be discussed in Unit 4.

rectilinear propagation the property of light that characterises it as travelling in a straight line in a uniform medium

Properties of light

Rectilinear propagation

In a homogenous (uniform) transparent medium, light travels in a straight line. This is known as **rectilinear propagation** of light and can be demonstrated by viewing the path of a laser light in air (Figure 2).

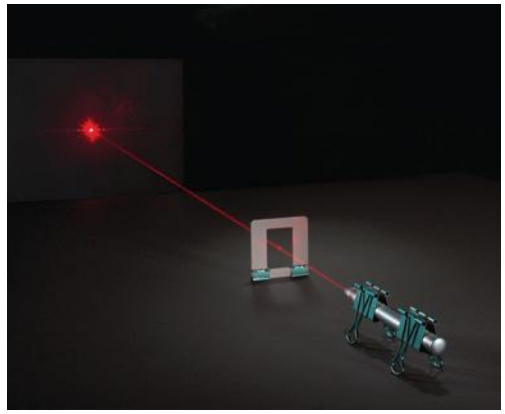

FIGURE 2 A laser beam travels in a straight line

Speed

The speed of light is a constant in a given medium and nothing can travel faster than light. In a vacuum, the speed of light is 2.998×10^8 m s^{-1}. However, light slows down when it moves through matter. The speed of light in water is about 2.25×10^8 m s^{-1}. In air, the slowing is quite negligible. For our calculations, we round off the speed of light to 3.0×10^8 m s^{-1} in a vacuum (or in air).

The **speed of light** in a vacuum (or in air): $c = 3.0 \times 10^8$ m s^{-1}

In this chapter, we will investigate the properties of light with respect to ray and wave characteristics – reflection and refraction for rays, and diffraction and interference for waves.

CHECK YOUR LEARNING 16.1

Describe and explain

1. **Recall** the speed of light in a vacuum.
2. **Explain** why light cannot be modelled as a mechanical wave.
3. **Recall** whether light needs a medium for its transmission.
4. **Describe** two examples of electromagnetic radiation.

Apply, analyse and interpret

5. On average, the Sun is 149.6 million kilometres away from us on Earth. **Determine** how long (in minutes) it takes light to travel from the Sun to Earth.
6. Physicists used to argue about which was the better model for light – the wave model or the particle model. **Reflect** on why they don't argue about this now.

Investigate, evaluate and communicate

7. **Predict** whether you could communicate on the Moon's surface using torches.
8. **Determine** if the Sun would look any different than it does at the moment if different colours of light travelled at different speeds.

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- » Student book questions
  Check your learning 16.1
- » Mandatory practical
  16.1 Refractive index of a transparent substance
- » Video
  Mandatory practical 16.1
- » Weblink
  Wave model of light

16.2 Light: a transverse wave

KEY IDEAS

In this section you will learn about:

- the transverse nature of electromagnetic waves
- polarisation.

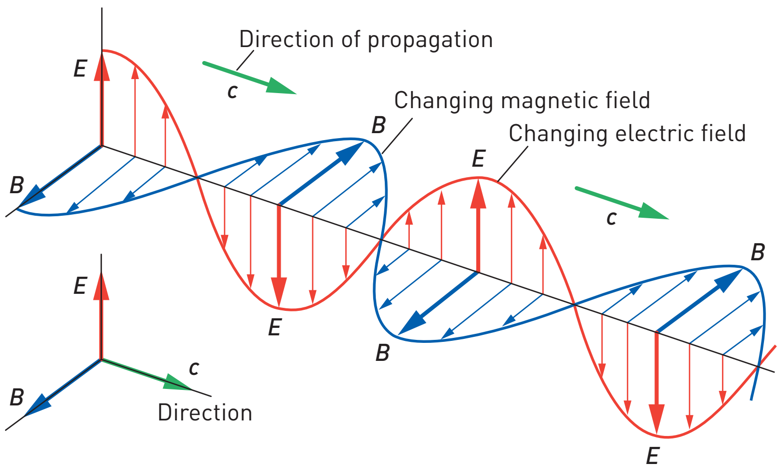

FIGURE 1 An electromagnetic wave changing magnetic and electric fields at right angles to each other and to the direction of propagation. The waves propagating in one direction only are shown here. In reality, they would be in all directions. The ***E*** and ***B*** arrows represent the electric and magnetic fields.

Scottish physicist James Clerk Maxwell (1831–1879) explained the nature of light waves based on electric and magnetic interactions, which is still the accepted theory today. He suggested the possibility of transverse electromagnetic waves propagating through space as changing electric and magnetic fields that are at right angles to each other (Figure 1).

Maxwell also developed general mathematical equations for these electromagnetic waves. The experimental value for the speed of light was found to be close to that predicted by his equations, suggesting that light was electromagnetic in origin. Maxwell's theory of electromagnetic waves was developed before he applied it to light.

In general terms, Maxwell suggested that electromagnetic waves are composed of two plane waves of equal amplitude, in phase, and at 90° to each other.

Polarisation

In 1669, Danish scientist Erasmus Bartholin reported the strange behaviour of light as it passed through a crystal of calcite – it split the ray in two. One beam passed through unchanged but the other was refracted and emerged parallel to the other beam. In 1690, Christiaan Huygens developed a wave theory of light that explained this double refraction, but it was not until 1704 that Isaac Newton gave it a name – **polarisation**. Newton said it was as if some of the particles of light were attracted like iron to the poles of a magnet.

polarisation (linear)
the process where light exists in the form of a plane wave in space (in contrast to unpolarised light, which is composed of two plane waves of equal amplitude, in phase, and at 90° to each other)

It wasn't until 100 years later that French army engineer Étienne-Louis Malus used the term 'polarised light' to explain the phenomenon. He established that polarisation was a property of the light wave and not of the crystal.

We know that light is modelled as transverse waves and has components of electric and magnetic fields in all directions. When all components of the electric fields except one are blocked, the wave is said to be plane polarised.

SUGGESTED PRACTICAL

16.2 Verifying the law of reflection – images in a plane mirror
Go to your obook assess »

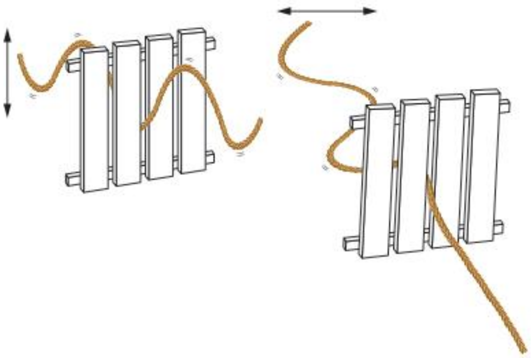

FIGURE 2 Transverse waves pass through the fence if the slit is in the same plane as the wave. When the waves are in another plane, they do not pass through.

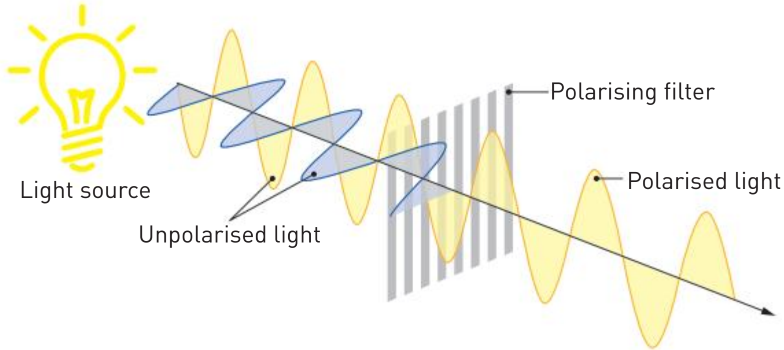

FIGURE 3 Polarisers allow only light waves in the plane of the polariser to pass through.

A device that allows only one component of the electric field through is called a **polariser**. A model for this is if a spring or a rope is threaded through a slit in a wall and is shaken in all directions; only those waves that are in the same plane as the slit will get through – the rest will be blocked. This is shown in Figures 2 and 3.

polariser
a device that allows only one component of the electric field to pass

We can measure the degree of polarisation of light by using a second polariser called an analyser (Figure 4).

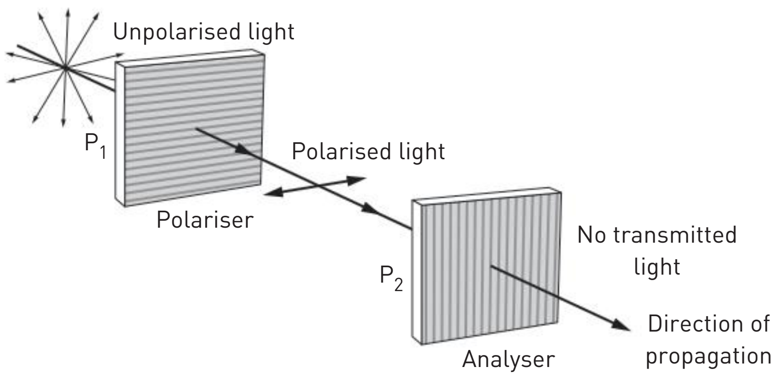

FIGURE 4 The angles between the polariser and the analyser determine the amount of light that is transmitted. In this case, the transmitted light will be zero, as the analyser is at right angles to the polariser.

'Polaroid' is the brand name of synthetic materials that have these polarising properties. These materials polarise light or allow light waves vibrating in one direction through. If an analyser is placed after the polariser (as shown in Figure 4), it is possible to block out all light from the source by rotating the analyser. If the plane of the analyser and the polariser align, light will be seen. If the plane of the analyser and the polariser are at right angles, no light will be transmitted through the analyser. The amount of light transmitted will vary between these two extremes depending on the angle between the planes of the polariser and the analyser.

FIGURE 5 Polarised sunglasses use lenses with polarising properties.

Polaroid uses

- Sunglasses – Polaroid sunglasses block annoying reflections from horizontal surfaces including wet roads and the ocean.
- Cameras – Crossed polarising filters can reduce the brightness of light entering a camera.
- Liquid crystal displays (LCDs) – The screens of calculators, phones, TV and digital watches use two pieces of polaroid that are crossed to produce dark symbols on a lighter background.
- Radio and TV waves – The electromagnetic radio and TV waves sent out from the big transmitters are usually polarised.

FIGURE 6 Sunlight is scattered by atoms in the atmosphere and the scattered light tends to oscillate in one direction so we say it is polarised. A polarising filter (right) removes most of the scattered light so the sky looks darker.

CHECK YOUR LEARNING 16.2

Describe and explain

1 **Describe** polarisation.

2 **Explain** how a polariser works.

3 **Describe** what would you notice if you were looking at reflected light off a pond with polarising glasses on and then turned the glasses slowly through 180°.

Apply, analyse and interpret

4 Placing two polarisers with their polarisation angles at 90° has an effect on the incident light. **Consider** how this might work.

Investigate, evaluate and communicate

5 **Design** an experiment to investigate the intensity of light through a pair of polarisers as one of the polarisers is rotated through 180°. Propose, with reasons, what the intensity vs angle relationship may look like.

6 **Propose** a test of whether the light directly from the Sun is polarised.

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» Student book questions
Check your learning 16.2

» Suggested practical
16.2 Verifying the law of reflection-images in a plane mirror

» Weblink
Everyday polarisation

» Weblink
Light as a wave

16.3 Intensity

KEY IDEAS

In this section you will learn about:

- intensity
- intensity and distance.

A light source, such as a bulb or the Sun, emits light in all directions. The total energy of all the light given off is termed the 'luminous flux'. People are usually interested in the amount of light falling on them – the energy falling on a given area in a given time. We are not as interested in the entire amount of energy given off by the source in all directions; we are interested in the **intensity** of the light received by us.

intensity
the average rate of flow of energy per unit area

We can develop a formula to help determine intensity. Firstly, power is the rate at which energy is transferred:

$$P = \frac{W}{t}$$

where W (work) is energy measured in joules (J); and P is power measured in watts (W) or joules per second (J s^{-1}).

Intensity is the power transferred per unit area, where the area is measured on the plane perpendicular to the direction of propagation of the energy:

$$I = \frac{P}{A}$$

where the quantity 'intensity' has the symbol I and the unit of watts per square metre (W m^{-2}).

WORKED EXAMPLE 16.3A

Calculate the intensity of a 100 W beam of radiation over an area 4.0 m^2.

SOLUTION

$$I = \frac{P}{A} = \frac{100}{4.0} = 25\ \text{W m}^{-2}$$

WORKED EXAMPLE 16.3B

A can containing 100 mL of water is placed near a high-intensity floodlight. The area of the can exposed to light is 8.0 cm × 15.0 cm and the energy delivered to the can was 1428 J in 5.0 minutes.

a What was the power of the radiation striking the surface of the can?

b What was the intensity of the radiation at the surface, assuming it was all converted to thermal energy?

SOLUTION

a $P = \frac{W}{t} = \frac{1428}{(5.0 \times 60)} = 4.8\ \text{W (2 sf)}$

b $I = \frac{P}{A} = \frac{4.8}{(0.080 \times 0.150)} = 400\ \text{W m}^{-2}\ \text{(2 sf)}$

Intensity and distance

The other aspect of interest is how the intensity of light falls off with distance. For example, point S has the source power of P_S watts (Figure 1) and that has radiated outwards in all directions (producing a spherical wave). The surface area A (in m^2) of the sphere at a distance r (radius) is given by the formula $4\pi r^2$. The amount of the source power per square metre on the surface is then:

$$\frac{P}{A} = \frac{P_S}{4\pi r^2}$$

which by definition is the intensity I.

At a distance of $2r$, the power is now spread over four times the area so the power per unit area is $\frac{1}{4}$ of the amount at r. Likewise, at a distance of $3r$ the intensity is $\frac{1}{9}$ of the intensity at r.

If a point source is radiating energy in all directions (producing a spherical wave), and no energy is absorbed or scattered by the medium, then the intensity decreases in proportion to distance from the object squared. This is an example of the inverse-square law.

$$I \propto \frac{1}{r^2}$$

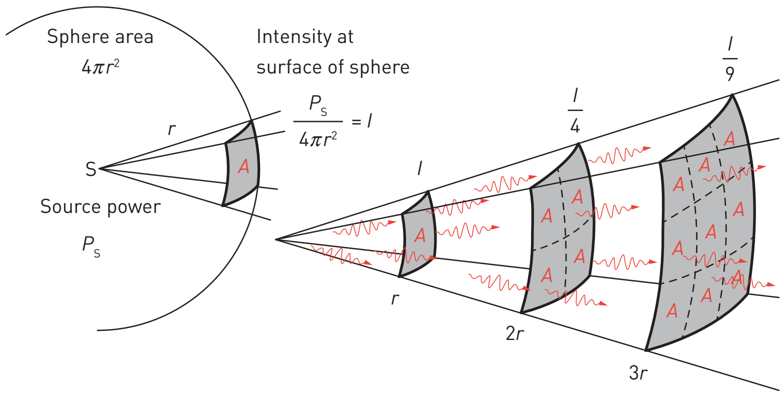

FIGURE 1 The energy twice as far from the source is spread over four times the area, hence one-quarter the intensity.

To compare the intensity I_1 at a distance r_1 from a source to the intensity I_2 at a distance r_2, we can use the relationship:

$$I_1 r_1^2 = \text{constant} = I_2 r_2^2$$

This can be rearranged to give:

$$\frac{I_1}{I_2} = \frac{r_2^2}{r_1^2}$$

For example, the intensity of radiation from the Sun is 1367 W m^{-2} at the distance of Earth (1 astronomical unit, AU) but is 9126 W m^{-2} at the distance of Mercury (0.387 AU). So, an approximate threefold increase in distance results in an approximate ninefold decrease in intensity of radiation.

This relationship holds if the medium the light is travelling through doesn't absorb or scatter the light. The presence of dust will have such an effect. This caused a big problem for astronomer Harlow Shapley in 1918. He was using a huge telescope at the Mount Wilson Observatory in California, United States, to measure the diameter of Earth's Milky Way galaxy. Shapley's estimate of 300 000 light years was far too large as he was unaware that there was so much intervening dust. Today, 100 000 light years is the accepted value.

WORKED EXAMPLE 16.3C

The street lights in Figure 2 are all 500 W sodium vapour lamps. A student is standing 20.0 m from the first light. Assuming no absorption or scattering of light:

a What is its intensity as measured from the student's position?

b Where would the student have to stand to measure the intensity as half this?

SOLUTION

a $I = \frac{P}{4\pi r^2} = \frac{500}{4\pi(20.0)^2} = 0.10\ \text{W m}^{-2}$ (2 sf)

b Halve the intensity:

$I = 0.05\ \text{W m}^{-2}$

$$\frac{I_1}{I_2} = \frac{r_2^{\,2}}{r_1^{\,2}}$$

$$\frac{0.10}{0.05} = \frac{r_2^{\,2}}{20.0^2}$$

$$r_2 = 28\ (2\ \text{sf})$$

r_2 = 28 m away from the light

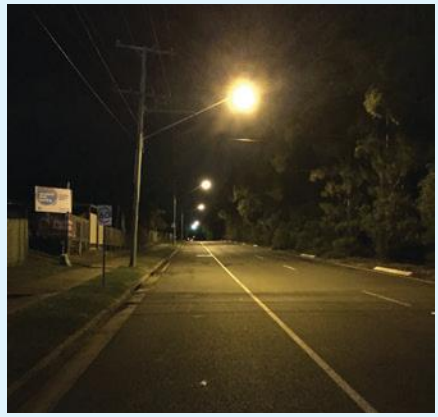

FIGURE 2 Sodium vapour lamps

CHECK YOUR LEARNING 16.3

Describe and explain

1 **Recall** whether intensity follows the inverse-square relationship with distance. **Explain** what this means.

Apply, analyse and interpret

2 The amount of sunlight reaching the surface of Earth on a particular day is 340 W m^{-2}.

- **a** **Calculate** how much power (in W) is received by a solar photovoltaic panel measuring 1.2 × 0.9 m on a roof.
- **b** **Calculate** how many 60 W light bulbs this is equivalent to.
- **c** **Determine** the intensity of the radiation.

3 **a** A bright torch has a light intensity of 15.0 W m^{-2} at a distance 1.00 m away. **Calculate** the intensity of the torch at 100.0 m distance.

- **b** **Determine** where the intensity would be half of what the intensity is at 100.0 m.

4 The intensity of a radio signal is 0.120 W m^{-2} at a distance of 16.0 m from a small transmitter. Without using a calculator, **determine** the intensity of the signal:

- **a** 8.0 m from the transmitter
- **b** 4.0 m from the transmitter.

5 A pet shop owner has a glass tank with an open top measuring 50.0 cm × 120.0 cm. The owner wants to illuminate the plants inside with light of 10 W and wants to know what wattage bulb to use in the light fitting 60.0 cm directly above the tank. **Determine** the value.

6 Assume the helium–neon lasers commonly used in student physics laboratories have power outputs of 0.50 mW.

- **a** A laser beam is projected onto a circular spot 1.00 mm in diameter. **Calculate** the intensity of the light at the spot.
- **b** An intensity of 100 W cm^{-2} is required to set fire to paper. **Deduce** how a laser beam could be made small enough to achieve this.

Investigate, evaluate and communicate

7 **Decide** if intensity and power are the same thing.

8 A student wants to start a fire from moonlight. Bright moonlight intensity is $\frac{1}{5\,000\,000}$ that of the Sun (Sun is 1000 W m^{-2}) so the student plans to use a lens of 5 m diameter and concentrate the light down to a 1 cm^2 spot. For a fire, the student needs 100 W cm^{-2} so they think it will work. **Evaluate** this proposal.

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Check your learning 16.3

» Weblink
Measuring intensity

» Weblink
Lamps and intensity

» Weblink
Intensity

16.4 Reflection in plane mirrors

KEY IDEAS

In this section you will learn about:

+ reflection in plane mirrors
+ ray diagrams for plane mirrors.

reflection
the process where incident waves at a boundary change direction, returning into the same medium according to the law of reflection

Most objects are seen by the **reflection** of light. The lake and mountains in the photo in Figure 1 are seen because the Sun illuminates them, and they reflect light to the eyes.

FIGURE 1 An early morning reflection on Lake Matheson at Fox Glacier, New Zealand. What is the difference between the real image and its reflection? Can you tell if this image has been rotated and is now upside down?

Sources of light

Light boxes and lasers are devices that can be used to produce beams or rays of light. Light boxes are common devices used in schools to produce thin beams or rays of light for the investigation of optics in the laboratory (Figure 2).

A laser can also be used as a source of light. Lasers emit light of one wavelength. You cannot see the light of a laser or the light from a light box unless the light strikes a wall or an object (including dust in the air). This is because your eye and brain only respond to light when it strikes your eye.

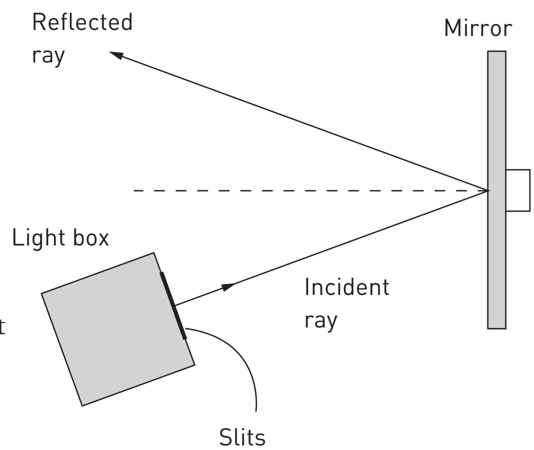

FIGURE 2 Light boxes that produce thin beams of light (rays) are used in laboratory optical investigations.

Plane mirrors

A plane mirror usually consists of a flat piece of glass that has its back coated with a thin layer of aluminium, and then a layer of paint to prevent the aluminium from flaking off.

Laws of reflection

What happens to a ray of light when it strikes a mirror? Everyone would say it is reflected, but in what way is it reflected?

The first law of reflection

The light ray that strikes the mirror is the incident ray, the ray that leaves the mirror is the reflected ray, and the perpendicular to the mirror is the normal (as shown in Figure 3). If you shine a laser at an angle into a mirror to provide the incident ray, this incident ray, the normal and the reflected ray all lie in the same plane. This is the first law of reflection. It can easily be demonstrated on a laboratory bench with the aid of a mirror, laser pointer and three rulers.

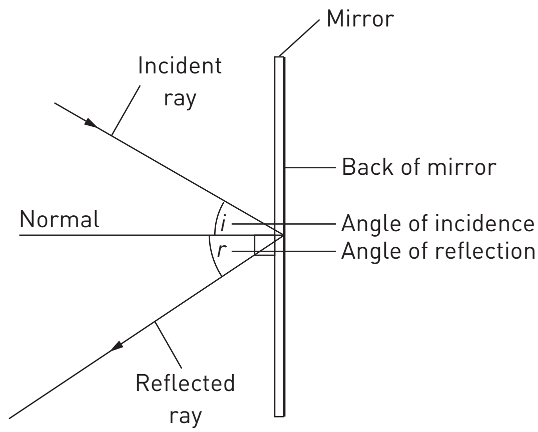

FIGURE 3 The common terms associated with rays of light and plane mirrors ($\angle i = \angle r$)

The second law of reflection

The angle between the incident ray and the normal is the angle of incidence, and the angle between the reflected ray and the normal is the angle of reflection (see Figure 3). Note that the angle of incidence equals the angle of reflection. This is the second law of reflection:

Second law of reflection for plane mirrors:

$$\angle i = \angle r$$

Images

When someone looks into the mirror, they see an image of themselves. The position of this image can be found with some investigation.

Consider looking at the image of the head of a pin in a plane mirror (Figure 4). The rays from the pin head reflect off the mirror and spread out (diverge) as they move towards your eyes. When your eyes see the rays, your brain projects them backwards to where the brain thinks they must have come from. These rays appear to meet behind the mirror and your brain interprets this as the location for the image of the pin head. The rays don't actually come from the image, but just appear to. For this reason, we call it a **virtual image**. The opposite of a virtual image is a **real image**.

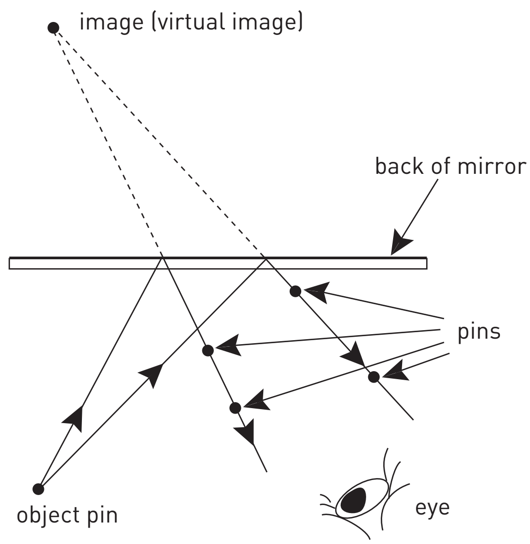

FIGURE 4 Two rays are needed to determine the position of the image (virtual image).

virtual image
an image through which the rays of light from the object do not actually pass but only appear to pass

real image
an image through which the rays of light from the object do actually pass

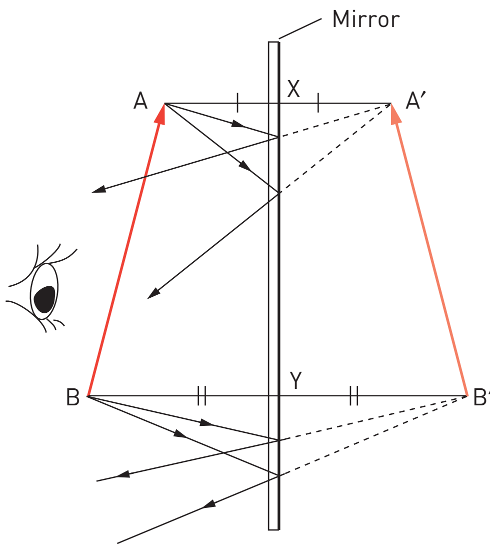

FIGURE 5 The red arrow AB represents a pencil. An image of the pencil is formed in the mirror, represented by the paler red arrow A′B′.

Examples of real images include the image seen on a cinema screen (the source being the projector), or the image produced on the retina of your eye when you look at something. The cornea and lens of your eye focus the rays of light from an object onto your retina. The rays of light actually strike your retina where the image is, so it is a real image.

Let's return to the formation of images by a plane mirror. If you study the ray diagram in Figure 4 you can confirm the following observations:

- the image is the same distance behind the mirror as the object is in front
- the line joining the object to the image is perpendicular to the mirror.

Let's now look at a solid object such as a pencil.

Figure 5 shows the image of an arrow AB (representing a pencil) in a mirror. The image of A can be established by using two rays from point A reflecting from the mirror to your eyes. The same applies to B. To position an object, two rays are needed. The brain uses the fact that light travels in straight lines and traces the rays back to where they appear to come from.

Notice in Figure 5 that arrow A'B' slopes the opposite way. This is because the image of an object lies the same distance behind a mirror as the object does in front and is on the perpendicular to the mirror. Therefore AX = XA', and BY = YB'. The same applies for all points between A and B. Notice also that the image A'B' is the same size as AB.

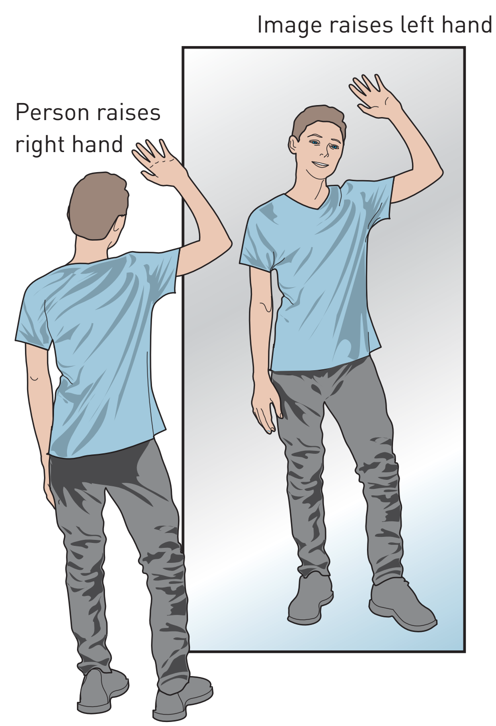

FIGURE 6 Lateral inversion in a plane mirror

Ray diagrams

Plane mirrors show an image that is laterally reversed. This can be observed by looking into a mirror and raising a hand (Figure 6). When a person raises their right hand, the image appears to raise its left hand.

This can be established by drawing ray diagrams (Figure 7). Object X is on the left and object Y is on the right. In the image, X' is on the image's right.

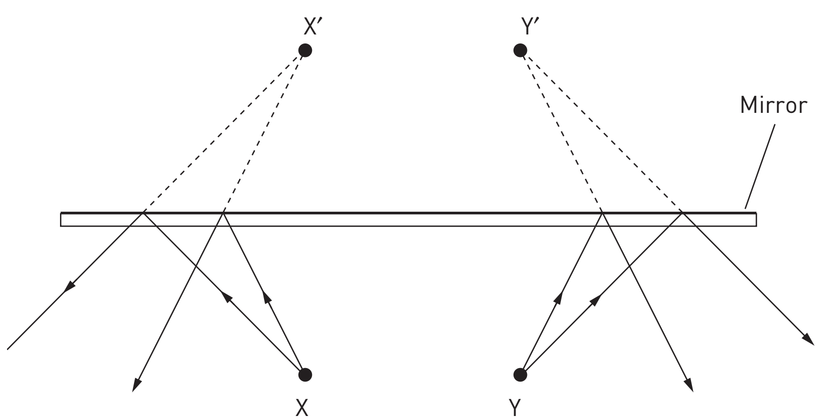

FIGURE 7 A ray diagram shows lateral inversion in a plane mirror

CHECK YOUR LEARNING 16.4

Describe and explain

1 **Describe** three significant optical facts about an image of yourself in a plane mirror.

2 One method of taking your own photo is to photograph your image in a large mirror. If you are standing 2.0 m in front of the mirror, **explain** how far away the camera would see the image.

3 **Explain** the difference between a real and a virtual image.

4 **Sketch** accurate ray diagrams to find the image of objects in the three cases shown in Figure 8.

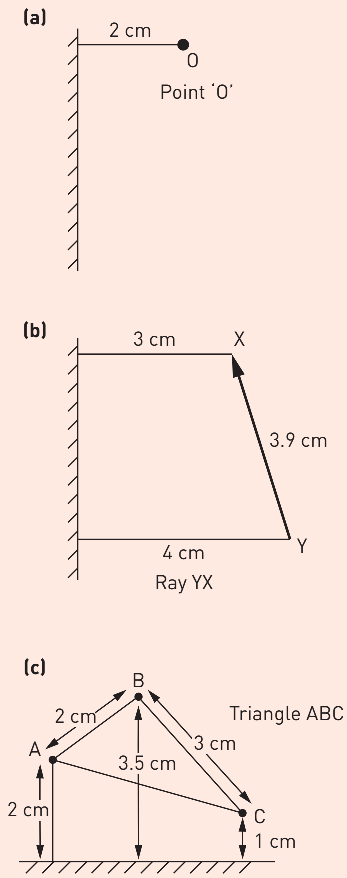

FIGURE 8 Sketch accurate ray diagrams.

5 For the three cases shown in Figure 9, **identify** the angle of incidence, the angle of reflection, the incident ray, the reflected ray and the normal.

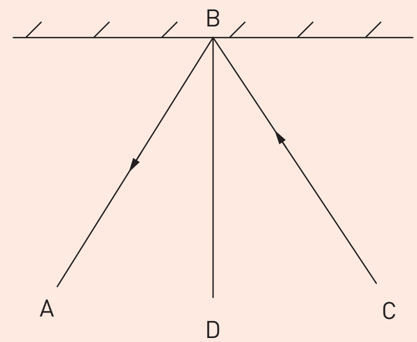

FIGURE 9 Ray diagram

Apply, analyse and interpret

6 **Deduce** why some police cars and ambulances have the words printed back to front, as shown in Figure 10.

FIGURE 10 Why are the words printed back to front?

7 If you wish to view your whole body in a mirror, **determine** what the minimum length the mirror would have to be and where on the wall it would need to be placed.

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- » Increase your knowledge
  Specular reflection
- » Increase your knowledge
  Diffuse reflection
- » Weblink
  Sources of light

16.5 Refraction of light

KEY IDEAS

In this section you will learn about:

- refraction of light
- Snell's law.

refraction
the process when incident waves at a boundary change direction and speed when passing into another medium

Early hunters took into account the refractive properties of water to accurately spear fish. As human understanding of **refraction** has developed, refraction of light is used in applications such as communication and medicine. The development of optical fibres has revolutionised the way we receive data from all over the world, and their use in exploratory surgery has reduced the amount of time we spend in hospital.

Refraction

Refraction is the changing in direction of waves as they go from one medium to another. For light waves, refraction occurs when light passes from one medium to another, such as when light rays pass from air to water, from air to glass or from glass to water. This direction change can be easily observed in the case of light – the light rays themselves bend at the boundary between the media.

In general, light rays bend toward the normal when they go from a less optically dense medium to a more optically dense medium. The reverse is also true – light rays bend away from the normal as they pass from a more optically dense medium to a less optically dense medium. This illustrates the reversibility properties of light rays through a refractive system.

It is the changing speed of light as it goes from air to the medium that determines the amount of refraction that occurs. Light travels faster in a vacuum or in air than in other mediums such as glass and water. This can be seen in Table 1.

TABLE 1 The velocity of light in various mediums of different refractive indices

Medium	Velocity of light in the medium, v ($\times 10^8$ m s^{-1})	Absolute refractive index of the material, n
Air	3.00	1.00
Ice	2.31	1.30
Water	2.26	1.33
Sea water (3.5% salt)	2.24	1.34
Ethyl alcohol	2.21	1.36
Fused quartz	2.05	1.46
Perspex	2.00	1.49
Benzene	2.00	1.50
Crown glass	1.97	1.52
Light flint glass	1.90	1.58
Heavy flint glass	1.82	1.65
Zircon	1.58	1.90
Diamond	1.24	2.42

Bending of light between mediums

Refraction can be explained using the analogy of a car hitting a flooded section of a road. As one of the car's front wheels hits the water, it slows down while the other wheel keeps going at the original speed (Figure 1). Therefore, the direction of the car changes – it bends into the water. The new direction of the car will be closer to the normal and it will slow down.

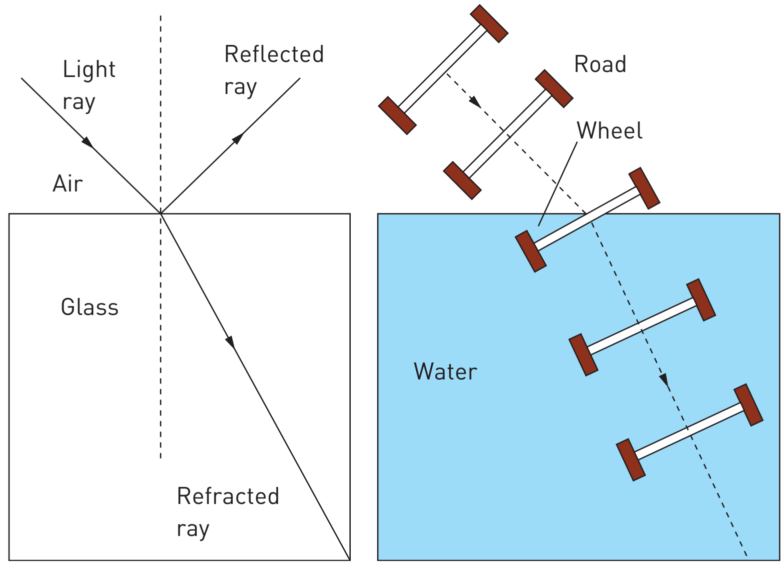

FIGURE 1 As the wheels of the car enter the water, they slow down and swerve towards the normal.

The ratio of the velocity in air to the velocity of light in a different medium is constant. This constant is called the **absolute refractive index** of the material. It is denoted by the symbol n, where v_a is the velocity of light in air and v_m is the velocity of light in the medium.

$$\frac{v_a}{v_m} = n$$

absolute refractive index
the ratio of the velocity of light in air to the velocity of light in a different medium

Snell's law

In 1621, Dutch mathematician Willebrord Snell (1580–1626) discovered that the refractive index of a substance can be found using the angles of incidence and refraction. Snell found that if the angle of incidence was changed, the angle of refraction also changed in such a way that the ratio of the sine of the angle of incidence to the sine of the angle of refraction is always a constant for a particular material. This constant is the absolute refractive index of the material. This is known as **Snell's law**:

Snell's law:

$$\frac{\sin i}{\sin r} = n$$

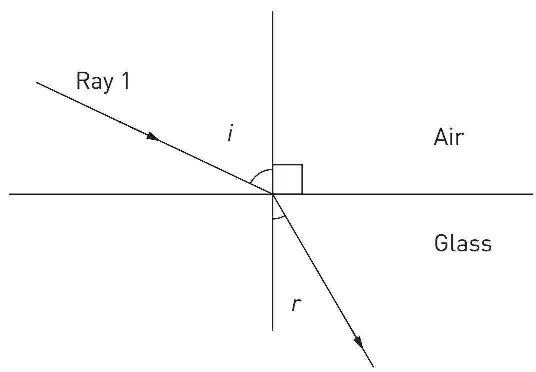

FIGURE 2 As light goes from air to glass it bends towards the normal.

Snell's law
when light travels from one medium to another, the ratio of the sine of the angle of incidence to the sine of the angle of refraction is equal to the refractive index

For example, imagine a ray of light entering a block of glass at an angle of incidence i and an angle of refraction r, as shown in Figure 2. Pairs of readings could be taken for angle i and angle r as shown in Table 2. Note that the ratio values of sin i to sin r is constant at about 1.50. Therefore, the refractive index of glass using the symbol n_{a-g}, $n_{a\rightarrow g}$, n_{ag} or just $n_g = 1.5$.

TABLE 2 Data for Figure 2

$\angle i°$	$\angle r°$	$\frac{\sin i}{\sin r}$
40	25	1.52
50	31	1.49
60	35	1.51

The refractive indices given in Table 1 are the absolute refractive indices – the refractive indices obtained when a light ray travels from air to the material. Knowing the value of the absolute refractive index and the angle of incidence, the angle of refraction can be determined.

WORKED EXAMPLE 16.5A

Light from a light box is shone onto a block of perspex at an angle of 30° to the normal. Determine the angle of refraction.

SOLUTION

$n_{perspex} = 1.4$

$\frac{\sin i}{\sin r} = n_{perspex}$

$\sin r = \frac{\sin i}{1.4}$

$= \frac{\sin 30°}{1.4}$

$= 0.357$

$r = 21°$

The absolute refractive indices in Table 1 are for light going from air to the material (such as glass, which is $n_{a\rightarrow g}$). But what is the refractive index of light passing from glass to air $n_{g\rightarrow a}$ as shown at the second surface in Figure 3?

Because of the reversible nature of light, $\angle r_1 = \angle i_2$, and $\angle i_1 = \angle r_2$.

Therefore, at surface 2:

$$n_{g\rightarrow a} = \frac{\sin i_2}{\sin r_2}$$

$$= \frac{1}{\frac{\sin r_2}{\sin i_2}}$$

$$= \frac{1}{\frac{\sin i_1}{\sin r_1}}$$

$$n_{g\rightarrow a} = \frac{1}{n_{a\rightarrow g}}$$

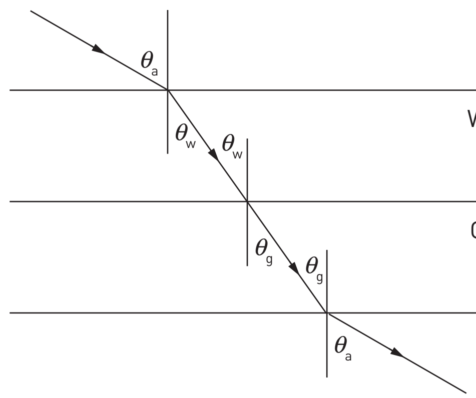

FIGURE 3 Because of the reciprocal law, light returns to its original angle before passing through different substances and emerging back into air.

This is called the **reciprocal law**.

reciprocal law
the refractive index for light passing from medium 1 to medium 2 is the reciprocal of the refractive index of light passing from medium 2 to medium 1

In general, the refractive index of light going from a material to air is the reciprocal of the absolute refractive index of the material:

$$n_{m\rightarrow a} = \frac{1}{n_{a\rightarrow m}} = \frac{1}{n_m}$$

WORKED EXAMPLE 16.5B

Find the refractive index of light going from glass to air.

SOLUTION

$n_{g\rightarrow a} = \frac{1}{n_{a\rightarrow g}}$

$= \frac{1}{1.50}$

$= 0.67$

If a ray of light passes from one medium to another, such as from water to glass, the ratio of the sine of the angle of incidence in water (n_w) to the sine of the angle of refraction in glass (n_g) is also a constant:

$$\frac{\sin\theta_a}{\sin\theta_w} = n_w \text{ and } \frac{\sin\theta_a}{\sin\theta_g} = n_g$$

$$\frac{\sin\theta_w}{\sin\theta_g} = \frac{n_g}{n_w} = n_{w\to g}$$

In general, the relative refractive index for light passing from medium 1 to medium 2 is given by the formula:

$$n_{1\to 2} = \frac{n_2}{n_1}$$

where $n_{1\to 2}$ is the relative refractive index for light going from medium 1 to medium 2, n_2 is the absolute refractive index for medium 2, and n_1 is the absolute refractive index for medium 1.

This results in a more general form of Snell's law, which can be used for light passing between any two media:

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$

Snell's law can be rearranged into a very useful form:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

WORKED EXAMPLE 16.5C

Find the angle of refraction for a ray of light passing from water to glass when the angle of incidence in water is 25°.

SOLUTION

$$n_w \sin\theta_w = n_g \sin\theta_g$$

$$1.33 \sin 25° = 1.5 \sin\theta_g$$

$$\frac{1.33 \sin 25°}{1.5} = \sin\theta_g$$

$$\theta_g = 22°$$

dispersion
the phenomenon in which the velocity of a wave depends on its frequency, and which is observed as the splitting of white light into a rainbow; this is due to the dependence of the index of refraction on the wavelength of light

Dispersion and colours

We know that white light is made up of all of the colours of the rainbow, but how is it that drops of water can cause the colours to separate out? The phenomenon is known as **dispersion**. Different colours have slightly different speeds in transparent substances such as water and glass. We know that the refractive index of light in a particular medium (n_m) depends on its speed in that medium (v_m) compared with its speed in air (v_a). This is shown by the formula:

$$n_m = \frac{v_a}{v_m}$$

Differing speeds results in each colour of light having a slightly different absolute refractive index. If white light is shone on the surface of a block of glass, the angle of refraction for each colour will be slightly different and the colours will separate slightly.

FIGURE 4 A continuous spectrum produced by the refraction of white light by a prism

spectrum
the range of frequencies of electromagnetic radiation and their respective wavelengths

If this occurs at a second surface, such as the second surface of a prism as shown in Figure 4, the effect is increased and results in a visible separation of the colours of light. The colour pattern formed is called a **spectrum** (from Latin meaning 'image'). Notice that violet light is refracted the most and red the least.

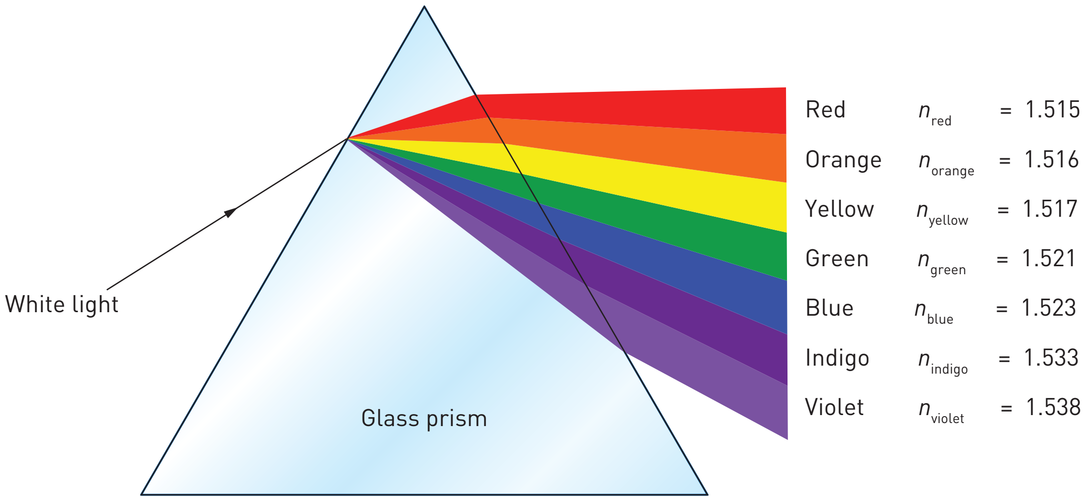

FIGURE 5 Because the different colours of light have different refractive indices, they separate when passing through a prism and create a spectrum. The path of the rays is only to show colour separation.

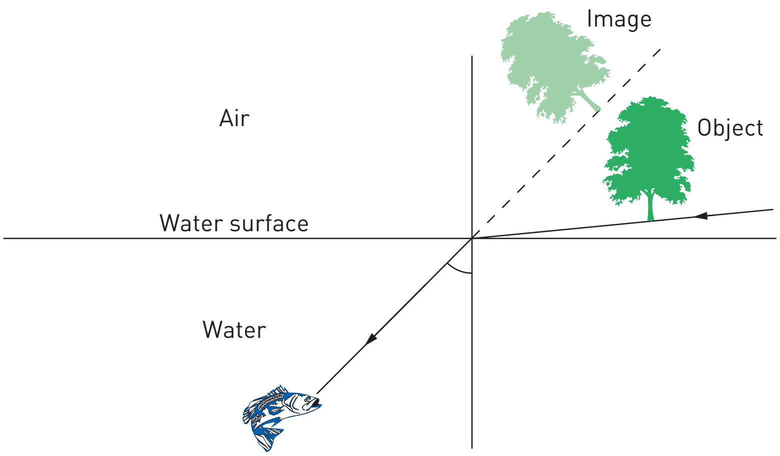

FIGURE 6 Because of refraction, fish see objects at positions that differ from their true positions.

Examples of refraction

Fish-eye view

To a fish or diver underwater, a tree on the shore would appear to be up in the air and objects would appear to be in different positions from where they actually are (Figure 6). This apparent difference in position is due to refraction. Certain fish can shoot down insects by squirting a high-pressure jet of water from their mouths toward their prey. These fish must take account of refraction to enable them to aim from under the water and hit the insect.

FIGURE 7 The pencils in the glass show light refraction

CHECK YOUR LEARNING 16.5

Describe and explain

1 **Explain** Snell's law.

2 **Describe** dispersion and account for its cause.

3 **Calculate** the index of refraction for light going from air ($v = 3 \times 10^8$ m s^{-1}) to a material in which its speed is:

a 2.6×10^8 m s^{-1}

b 1.8×10^8 m s^{-1}.

4 **Calculate** the speed of light in a medium whose refractive index is:

a 1.5   b 2.4   c 1.3.

5 Calculate the refractive index of the material shown in Figure 8.

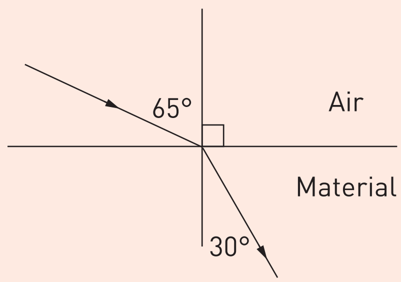

FIGURE 8 What is the refractive index of the material?

6 **Calculate** the refractive index for light passing from water ($n = 1.33$) to crown glass ($n = 1.52$).

Apply, analyse and interpret

7 A drop of soapy water ($n_{soapy\ water} = 1.38$) was placed onto a block of glass ($n_g = 1.5$), as shown in Figure 9. A ray from a laser was shone onto the water at an angle of 38°.

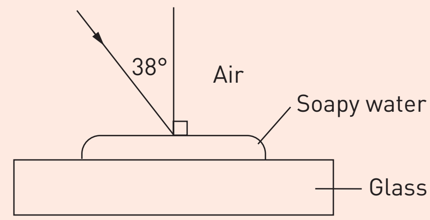

FIGURE 9 A drop of soapy water on a block of glass

Determine:

a the angle of refraction in the soapy water

b the angle of refraction in the glass

c the angle at which the ray exited from the glass

d the relative refractive index of light going from soapy water to glass.

Investigate, evaluate and communicate

8 **Predict** whether rays of light bend towards the normal in the following media pairs:

a glass to water

b glass to diamond

c alcohol to water

d perspex to heavy flint glass.

Check your obook assess for these additional resources and more:

- » Student book questions
  Check your learning 16.5
- » Video
  Refraction in a semicircular block
- » Video worksheet
  Refraction in a semicircular block
- » Increase your knowledge
  Refraction of light

16.6 Total internal reflection

KEY IDEAS

In this section you will learn about:

+ total internal reflection
+ critical angle.

When light passes from a more dense to a less dense medium, it bends away from the normal. However, when the refracted ray is 90° or more, the incident ray is totally reflected, producing **total internal reflection**.

total internal reflection
the phenomenon whereby all energy is reflected inside a medium due to the incident angle of the wave being greater than the critical angle

critical angle
the angle of incidence (symbol θ_c) for light in a more optically dense medium for which the angle of refraction in the less optically dense medium is 90°, resulting in total internal reflection

As previously discussed, a ray of light bends toward the normal when going from a less dense to a denser medium. The opposite is also true. Rays will bend away from the normal when going from a denser to a less dense medium. This results in an odd situation as the angle of incidence increases as shown in Figure 1.

There comes a stage where the angle of refraction is 90° (Figure 1(d)). The angle of incidence that produces this is called the **critical angle** (θ_c). If the angle of incidence is further increased, the ray of light is entirely reflected from the surface at an angle equal to the angle of incidence. This is called total internal reflection and occurs when light travels from a more optically dense medium to a less optically dense medium and the angle of incidence is greater than the critical angle.

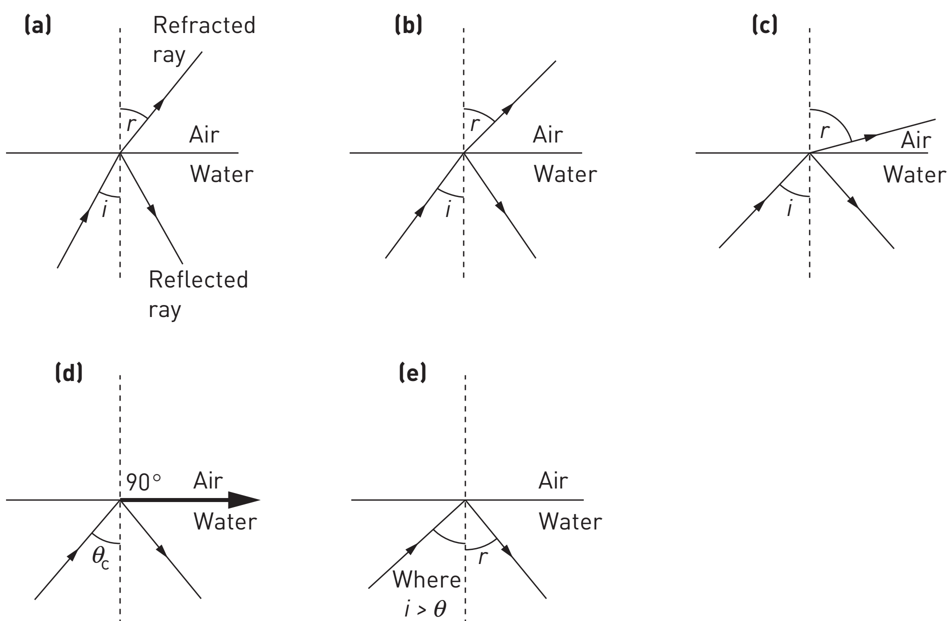

FIGURE 1 Diagrams showing the passage of light from water to air for increasing angles of incidence

For a ray of light going from water to air:

$$\frac{\sin\theta_w}{\sin\theta_a} = n_{w\to a} = \frac{1}{n_w}$$

When the angle of incidence θ_w is equal to the critical angle θ_c, the refracted angle θ_a = 90°, and sin 90° = 1. Then, when the less dense medium is air:

$$\sin\theta_c = \frac{1}{n_w}$$

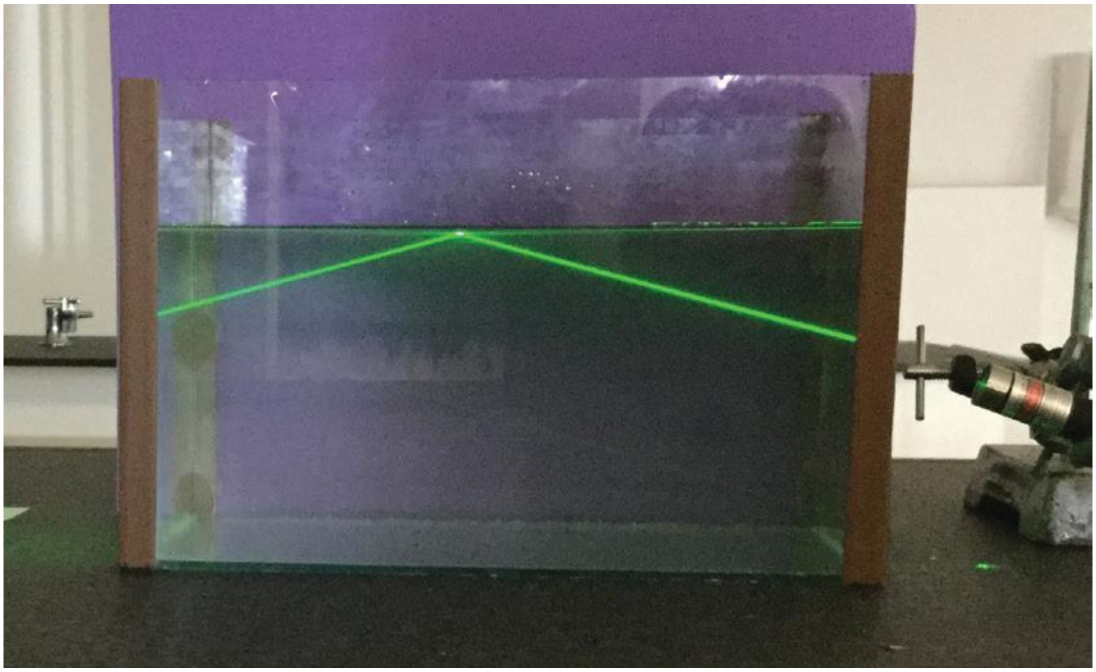

FIGURE 2 A green laser beam enters the fish tank of water, but the angle of incidence is too large for it to escape out into the air at the top. Hence, the light totally reflects off the underside of the water surface. This is total internal reflection.

WORKED EXAMPLE 16.6

Find the critical angle for a light ray passing from light flint glass (n = 1.58) to:

a air (n = 1.00)

b water (n = 1.33).

SOLUTION

a As the less dense medium is air, we can use the following formula:

$$\sin\theta_c = \frac{1}{n_g}$$

$$= \frac{1}{1.58}$$

$$\theta_c = 39.3°$$

b As the less dense medium is not air, we need to use the full formula in which medium 1 is the flint glass and medium 2 (the less dense medium) is water:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

$$1.58 \sin\theta_c = 1.33 \sin 90°$$

$$\sin\theta_c = \frac{1.33 \times \sin 90°}{1.58}$$

$$\theta_c = 57.3°$$

Total internal reflection can be demonstrated easily by using a semicircular block of glass and a light box (Figure 3). The block is placed on a sheet of white paper and a ray from a light box is directed from the top onto the centre of the semicircular block. The ray entering the glass is along a radius and is perpendicular to the surface, therefore no refraction occurs at the first surface. Refraction occurs at the second surface and the ray bends away from the normal. As the angle of incidence at this surface is increased, the angle of refraction also increases. When the angle of incidence is approximately 42°, the refracted beam will be

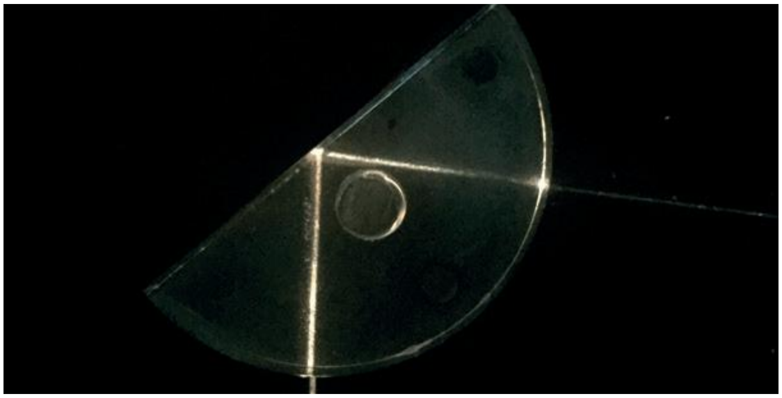

FIGURE 3 Total internal reflection produced by light passing from glass to air

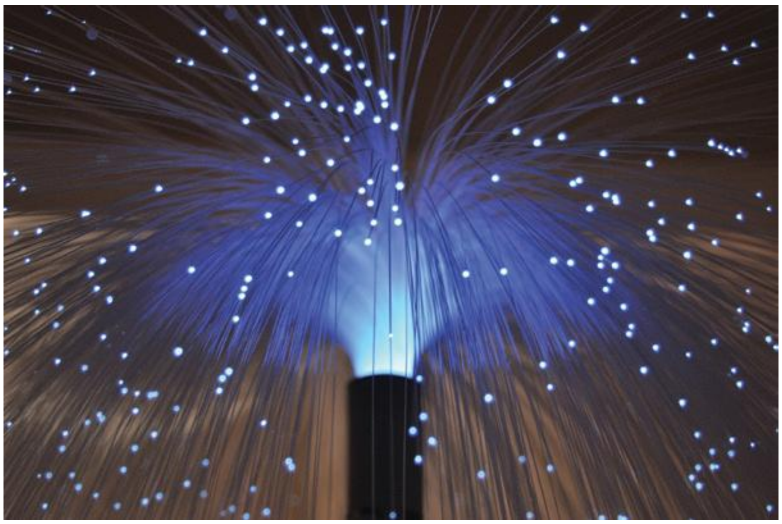

FIGURE 4 Optical fibre lamp

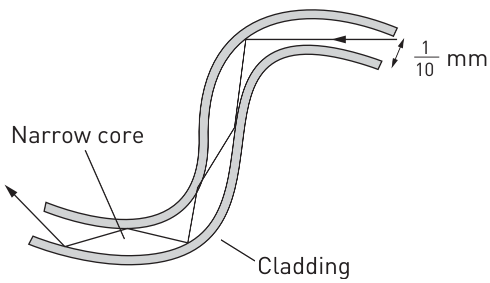

FIGURE 5 An optical fibre consists of a thin glass fibre of higher refractive index than the outside cladding layer. Thus, total internal reflection is used to reflect light pulses along the length of the fibre.

along the straight surface of the block of glass – that is, the angle of refraction is 90°. If the angle of incidence is made slightly greater, the refracted beam disappears as the light beam is reflected back inside the block of glass at an angle equal to the angle of incidence. This is total internal reflection.

Uses of total internal reflection

Optical fibres

One of the major developing uses of total internal reflection is in optical fibres. Fibre optics is a branch of optics dealing with the transmission of light through fibres or thin rods of glass, or through some other transparent material of high refractive index. Light is admitted at one end of a fibre and travels through the fibre with very low loss, even if the fibre is curved.

An optical fibre (Figure 5) consists of a very pure glass fibre as thin as a hair (0.125 mm) with a layer of cladding around the outside to protect it from damage and moisture.

The outside layer has a lower refractive index than the inside material, thus creating a situation where light propagating in the central layer is travelling in a more dense material than in the outside layer. Light is totally internally reflected if it strikes the boundary between the two media at an angle greater than the critical angle. Light is reflected along the length of the fibre, which can be bent into any shape as long as it is not kinked. Once kinked, the surface cracks allow light to refract out.

The medical profession was the first to make use of optical fibres. Surgeons use bundles of fibres to look inside a person's stomach and lungs without surgery. A bundle of fibres is introduced into the stomach via the throat. Light is shone down some of the fibres and reflected light from the stomach is transmitted back via other fibres.

The telecommunications industry was one of the first large commercial users of optical fibres. Digital electrical signals are converted into light pulses and transmitted over optical fibre cable by switching light-emitting or laser diodes on and off. At the other end, these optical digital pulses are converted back into electrical signals by photo-transistors.

Study tip

Information about mirages and rainbows can be found on your obook assess.

CHALLENGE 16.6

Colourful bacon

Have you noticed the green iridescent colours that sometimes appear on bacon and corned meat? This is not necessarily rotting meat! The appearance is caused by microscopic droplets of oil and water of differing refractive indices on the surface causing the interference of light. If it goes really green, that's the bacteria breaking down the oxygen transport protein (myoglobin) to produce green compounds. Heat will show the difference as it will make the oil droplets go away but not the green rot. Why is there green iridescence and not red or violet?

CHECK YOUR LEARNING 16.6

Describe and explain

1 **Explain** the conditions for total internal reflection to occur.

2 **Describe** how an optical fibre transmits a light signal over long distances with a low loss of energy.

3 A block of ice is placed on top of a semicircular block of crown glass (Figure 6). **Calculate** at what minimum angle all incident light on the boundary between the two surfaces would be reflected.

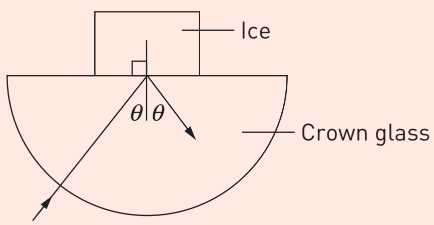

FIGURE 6 Block of ice on top of a semicircular block of crown glass

4 A ray of light travels from one medium to another. It is found that total internal reflection occurs when the incident angle is greater than 54°. If the refractive index of the first medium is 1.49, **calculate** the refractive index of the second medium.

Apply, analyse and interpret

5 In each of the following situations where a light ray passes from one medium to another, **determine** whether it is possible for total internal reflection to take place and **explain** why.

a air to glass
b diamond to air
c water to glass
d flint glass to air
e ice to a vacuum
f crown glass to perspex

6 Optical fibres have a less optically dense layer surrounding the fibre in order to produce total internal reflection. If the fibre has a refractive index of 1.70 and the outside cladding layer has a refractive index of 1.48:

a **calculate** the minimum angle at which light incident on the junction is totally internally reflected
b **determine** the speed of light in the fibre.

Investigate, evaluate and communicate

7 Students investigating total internal reflection using a semicircular block of glass notice that there is a faint reflected beam before total internal reflection occurs. **Discuss** the intensity of beams (i), (ii) and (iii) in Figure 7 as the angle of incidence increases.

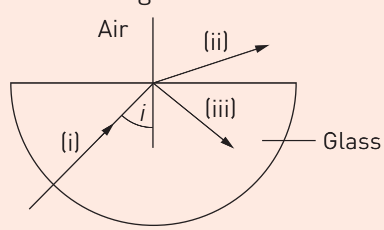

FIGURE 7 Total internal reflection experiment using a semicircular block of glass

Check your obook assess for these additional resources and more:

» Student book questions
Check your learning 16.6

» Challenge
16.6 Colourful bacon

» Increase your knowledge
Mirages and rainbows

» Weblink
Endoscopes – optical fibres

16.7 Ray diagrams and lenses

KEY IDEAS

In this section you will learn about:

- ray diagrams for lenses
- images formed by concave and convex lenses.

FIGURE 1 *Anableps* is a Central American fish that has two retinas per eyeball and egg-shaped lenses. It swims just below the surface of the water with its large eyeballs protruding half above and half under the water. Because of the difference in refraction that occurs when light passes from air to the eye, and from water to the eye, images occur at different distances from the lens, thus requiring retinas at different positions.

Lenses play a major part in everyday life and in the scientific world. They are present in glasses, contact lenses, phones, cameras, microscopes, telescopes and photocopiers, to name a few. Simple hand-lenses are used in science classes for mineral identification and looking at cells and crystals.

Lenses are transparent devices that refract light. Different shaped lenses refract light differently. Once they were made of glass but now, to reduce the weight, most lenses are made of plastic.

Shapes of lenses

The two main lens shapes are concave and convex (Figure 2). The earliest spectacles reminded their makers of the beans called lentils, hence the term *lens*, from the Latin for 'lentil beans'.

Light incident on a lens always bends toward the thickest part. Recall the refraction of light through a prism (Figure 3). Light is refracted toward the normal at the first surface and away from the normal at the second surface. The overall effect is that light always bends toward the thickest part of the prism.

converging
bending of light rays together

converging lens
a lens that converges light (convex lens)

A lens can be thought of as a system of tiny prisms of slightly different shapes so that light rays are refracted at both sides of the lens, which results in the bending of light rays toward the thickest part. Light rays incident on a convex lens bend toward the centre, thus focusing or **converging** the light. For this reason, a convex lens is also called a **converging lens**.

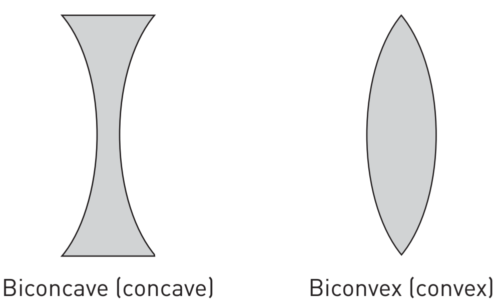

FIGURE 2 Shapes of two common lens types – concave and convex

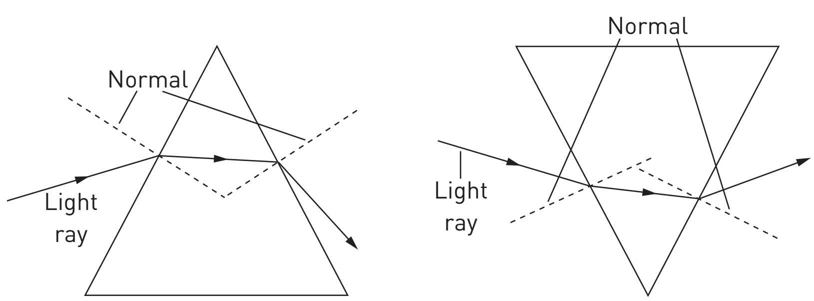

FIGURE 3 Light through a prism always refracts toward the thickest part of the prism.

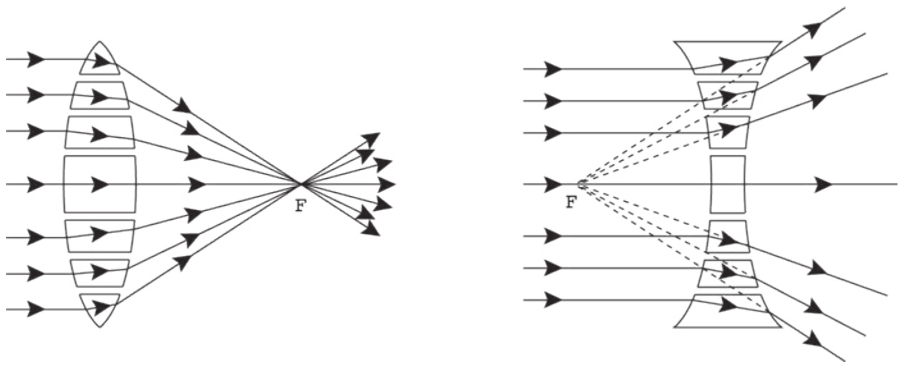

FIGURE 4 Lenses can be considered to be made up of tiny prisms, thus light will always refract towards the thickest part of the lens. (a) The convex lens converges light, so it is a converging lens. (b) A concave lens, which is a diverging lens.

Study tip

Remember lens shapes as 'con**cave** goes in like a cave'.

Light incident on a concave lens spreads or **diverges** the light, hence a concave lens is also called a **diverging lens** (Figure 4).

diverges
bends light rays away from each other

diverging lens
a lens that diverges light (concave lens)

Features of lenses

Curved lenses look like parts of the circumference of circles. We can use simple geometry to represent lenses.

Each face of the lens can be drawn using a compass. The centre of the circle that produces the curved surface is called the **centre of curvature**. Each face can have a different curvature. However, for our discussions we will use lenses whose sides have the same radius of curvature.

centre of curvature
the centre of the circle that produces the curved surface of a lens

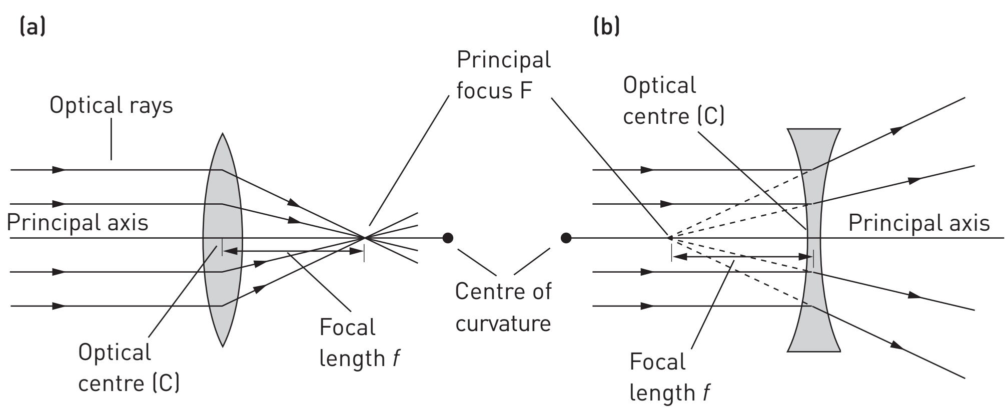

FIGURE 5 The main terms associated with lenses

Figure 5 shows the main features of lenses. The line joining the centre of curvature through the optical centre of the lens is called the **principal axis**. If rays of light parallel to the principal axis are incident on a convex lens, the rays converge to a point on the other side of the lens called the **principal focus** (F). Since lenses can be used either way around, they have two focal points – one on either side of the lens. If rays of light parallel to the principal axis are incident on a concave lens, they diverge. However, if these rays are traced back they appear to come from a point on the same side of the lens as the light originates. This is a virtual focus. The distance from the focal point to the optical centre of the lens is the **focal length** (f).

principal axis
the line joining the centre of curvature through the optical centre of the lens

principal focus
a point where incident rays of light parallel to the principal axis converge to a point on the other side of a converging lens, or where the rays appear to have diverged from for a diverging lens

focal length
the distance between the centre of a lens and its principal focus

Thicker lenses have a shorter focal length, as shown in Figure 6.

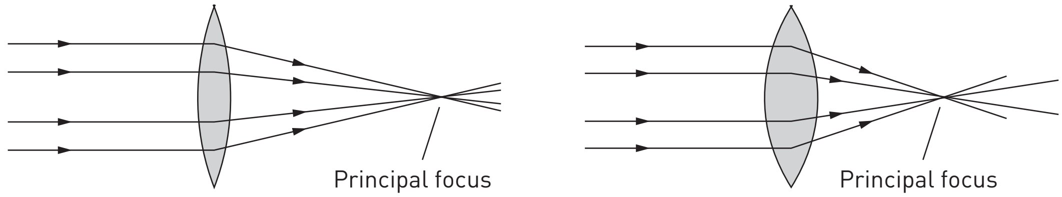

FIGURE 6 Thick lenses have shorter focal lengths than thin lenses and therefore are more powerful.

Ray diagrams and images

If you look through a magnifying glass (a convex lens) at an object, you can see the object. In actual fact you are only seeing the image of the object. This can be easily verified if you look at an object a long distance away while holding the lens at arm's length. The image is inverted (upside-down).

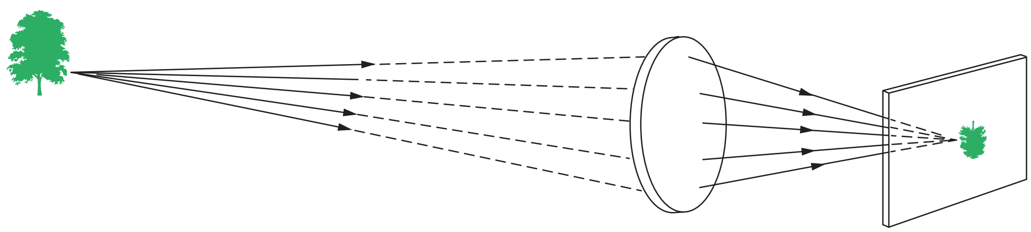

FIGURE 7 Images of distant objects are inverted, indicating that when you look through a lens you are observing the image and not the object itself.

Using ray diagrams

Ray diagrams can be drawn to find the position and nature of an image. Although refraction occurs at both sides of the lens, we simplify the drawing of ray diagrams by drawing a line through the centre of the lens and have all refraction occur at this line.

Any number of rays can be drawn to determine the position and nature of the image, but to produce an accurate ray diagram often requires the use of protractors, calculations and measurements of the angles of refraction at both surfaces. For this reason, three rays are most commonly used to simplify the drawing of ray diagrams:

1 The ray parallel to the principal axis that refracts through the principal focus for a convex lens and appears to come from the focus for the concave lens.

2 The ray through the focus that refracts parallel to the principal axis for the convex lens. For a concave lens, the ray that is lined up with the focus on the opposite side refracts parallel to the principal axis.

3 The ray through the centre of the lens that continues unchanged in direction.

To find the position of an image requires the use of two rays – the third ray can be used to double-check the position.

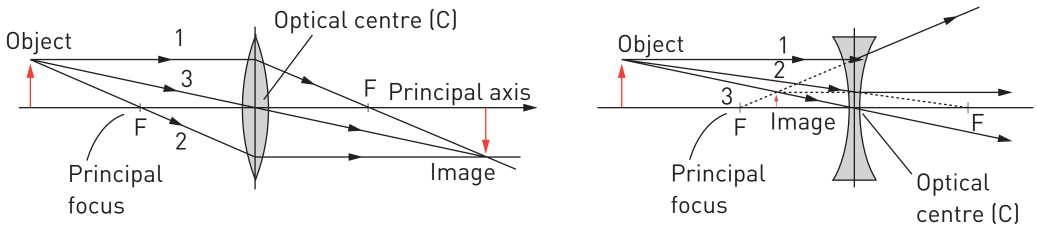

FIGURE 8 The three rays used to find the image produced by a lens – a ray parallel to the principal axis (1), a ray through the focal point (2), and a ray through the optical centre of the lens (3). You can represent the lens by just a straight vertical line.

CHALLENGE 16.7

Mirrors and lenses in water

A concave mirror and a convex lens are placed in water. Does their focal length change? Why or why not?

Characteristics of the image

When you draw a ray diagram, you will be expected to state the 'nature, location, orientation and size' of an image.

- **nature** – whether it is real (rays pass through the image) or virtual (rays only appear to pass through the image)
- **location** – where it is in relation to the lens, usually stated in centimetres in front of the lens (same side as the object) or behind the lens (opposite side to the object)
- **orientation** – whether it is upright or inverted (upside-down)
- **size** – whether it is bigger (enlarged) or smaller (diminished) compared with the object. Terms used to describe an image larger than the object include 'magnified', 'enlarged' or 'bigger'. When the image is smaller than the object we say it is 'smaller' or 'diminished'.

Images in convex lenses

Figure 9 shows some examples of ray diagrams. The object has been placed at various positions with respect to the convex lens: greater than $2f$, at $2f$, between $2f$ and F, and between F and the lens. The ray diagrams show the following:

Figure 9(a): When the object is outside $2f$, the image produced is real, inverted, smaller, and between F and $2f$ on the opposite side of the lens.

Figure 9(b): When the object is at $2f$, the image produced is real, inverted, the same size, and at $2f$ on the opposite side of the lens.

Figure 9(c): When the object is between $2f$ and F, the image produced is real, inverted, larger, and outside $2f$ on the opposite side of the lens.

Figure 9(d): When the object is between F and the lens, the image produced is virtual, upright, larger, and between F and the lens on the same side of the lens.

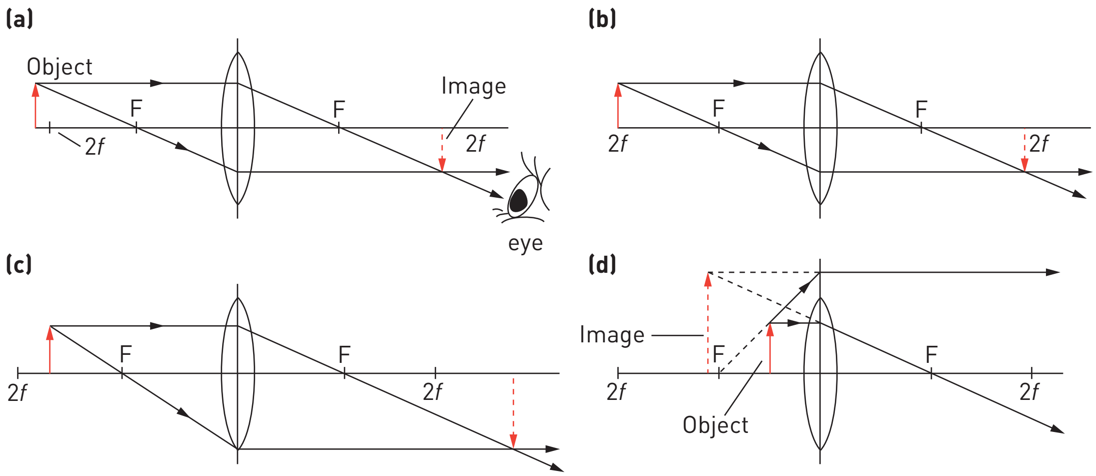

FIGURE 9 Ray diagrams for an object placed at various positions relative to a convex lens: (a) greater than 2*f*, (b) at 2*f*, (c) between 2*f* and F, and (d) between F and the lens

As an object moves toward F, the image moves away from the convex lens and increases in size. When the object is between F and the convex lens, a virtual image is formed.

Images in concave lenses

The same three rays can be used to find the position and nature of an image in a concave lens. However, two important rules must be remembered:

- The rays always bend toward the thickest part of the lens.
- The focal point (the point where light rays parallel to the principal axis converge or appear to come from), is on the same side of the lens as the object.

Figure 10 shows the use of rays to find the position and characteristics of the image in a concave lens. The ray diagrams show the following:

Figure 10(a): When the object is at a distance from the concave lens, the image produced is virtual, upright, smaller, and between F and the lens on the same side of the lens.

Figure 10(b): When the object is close to a concave lens, the image produced is virtual, upright, smaller, and between F and the lens on the same side of the lens.

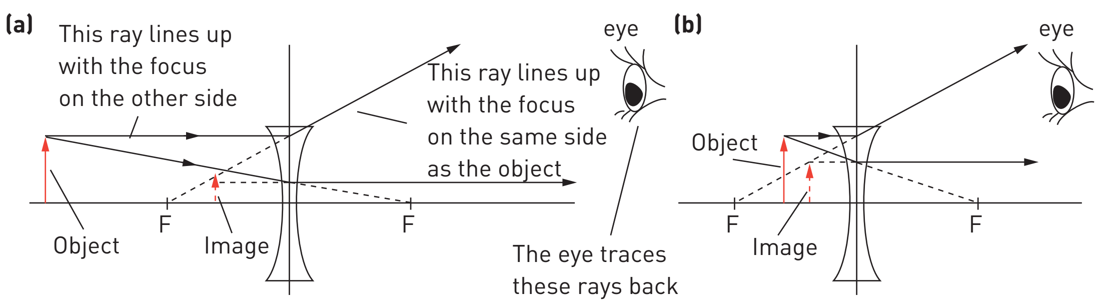

FIGURE 10 Ray diagrams for an object placed at various positions relative to a convex lens

Study tip

Extra challenges involving lenses can be found on your obook assess.

You will notice that whatever the distance of the object, even close to the lens, the image is virtual, upright, smaller and between the lens and F on the same side as the object. Concave lenses always produce these types of images no matter where the object is placed.

CHECK YOUR LEARNING 16.7

Describe and explain

1 **Sketch** diagrams to represent convex and concave lenses.

2 For the ray diagram shown in Figure 11:

a **determine** the following: focal point, 2*f*, object, image, object height, optical centre, image distance, object distance

b **determine** the location, orientation and size of the image.

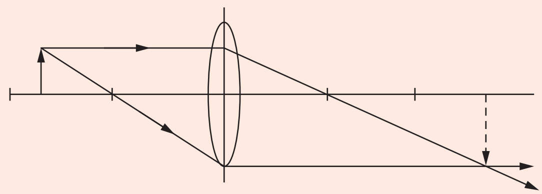

FIGURE 11 Ray diagram

3 A 2.0 cm high candle is placed 50 cm in front of a 20 cm focal length convex lens. **Sketch** a ray diagram to find:

a the location of the image

b the magnification

c the height of the image

d the location of the image of the candle if it is placed inside the focal point at a point 10 cm from the lens.

Apply, analyse and interpret

4 **Infer** the path of light in the ray diagrams shown in Figure 12.

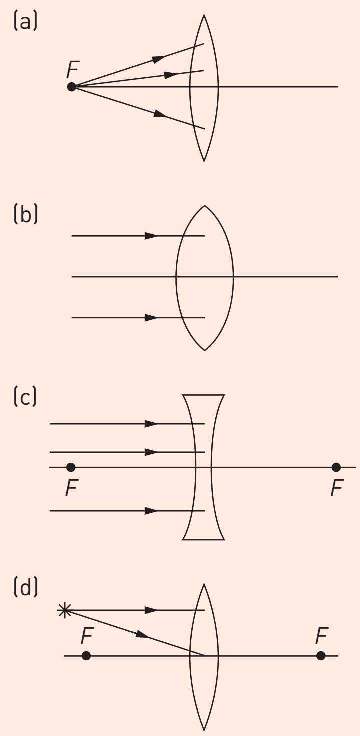

FIGURE 12 Ray diagrams

5 An object 5.0 cm high is placed 20.0 cm from a convex lens of focal length 15.0 cm. **Sketch** a ray diagram to scale to **determine** the nature, location, orientation and size of the image.

6 Use a ray diagram to **determine** the nature, location, orientation and size of the image of a 5.0 cm high object placed 25.0 cm in front of a concave lens of 10.0 cm focal length. (Use a scale of 1 cm = 5 cm.)

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16.8 Diffraction and interference of light

KEY IDEAS

In this section you will learn about:

+ diffraction of light
+ interference of light.

Both the wave model and the particle model are useful for describing some properties of light, such as how images form. However, diffraction and interference are two characteristics of light that can only be explained by the wave model of light.

Diffraction

diffraction the process by which waves either bend behind a barrier or the wavefront is broken up into many small sources

In chapter 14 we saw that **diffraction** is the bending of waves as they pass through an aperture or around the edge of an object in their path. This bending of waves is more noticeable if the wavelength of the waves is comparable to the size of the opening. If an object is placed in the path of the waves, a 'shadow' is produced if the object is of the same size as the wavelength. To observe this effect, the slit or the object in front of the waves has to be of the same size as the wavelength of the waves, and light waves have very short wavelengths.

Light does bend around the edges of objects to produce diffraction 'fringes'. Objects seem to be blurred at the edges when light shone on them is focused on a screen. Figure 1 shows the diffraction fringes produced by red light passing the edges of a razor blade. This explains why it is difficult to look at objects as small as the wavelength of light (such as atoms) with a microscope. They just look blurred.

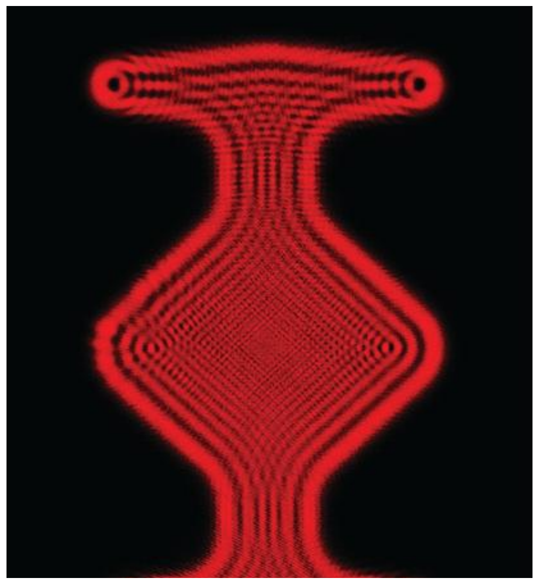

FIGURE 1 Diffraction fringes produced by red laser light passing the inside edges of a razor blade

Interference

interference the combination of two or more waves to form a resultant wave

A striking example of the diffraction effect can be seen when light passes through two narrows slits side by side. For example, at night in rainy weather, scratches on a car's windscreen produce long shafts of light with black bands across them. This is a result of diffraction of the light as it passes through the slits and the **interference** of light afterwards.

This pattern can be seen more clearly if a laser and commercially prepared narrow slits are used. If different colours of light are used, the pattern changes. If red light is used, the pattern spreads out more than when blue light is used. Recall the diffraction of water waves – the larger the wavelength compared with the slit, the more the pattern spreads out and the more noticeable the diffraction is. This suggests that the wavelength of red light is larger than that of blue light.

Diffraction of light is also produced when light passes through a single slit, but it is not as dramatic. Figure 2 shows the diffraction pattern produced on a screen when white light passes through a very narrow single slit.

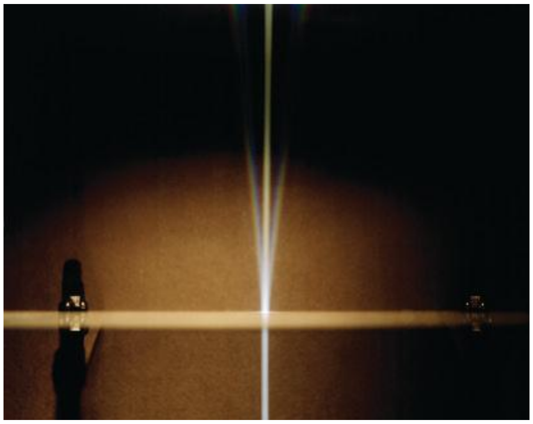

FIGURE 2 The diffraction pattern of white light passed through a narrow slit

FIGURE 3 The Christmas beetle (*Anoplognathus pallidicollis*) displays colourful iridescence, which can be explained by the interference of light waves in its exoskeleton.

These banding effects can be explained by constructive and destructive interference of the light passing through the slits. For example, a wavefront striking a slit becomes a new circular wave on the other side. With two slits, these two circular waves overlap and regions of constructive interference and destructive interference are produced. Constructive interference occurs when the waves are in phase and is responsible for the bright light and colours, whereas the dark regions are a result of destructive interference due to the waves being out of phase.

The first person to come to a theoretical understanding of how this diffraction and interference works was English academic Thomas Young (1773–1829).

CHECK YOUR LEARNING 16.8

Describe and explain

1 **Describe** how the wave model helps explain the phenomena of diffraction.

2 **Describe** how the wave model helps explain interference of light.

Apply, analyse and interpret

3 **Explain** whether blue or orange light would undergo more diffraction. Orange light has a longer wavelength than blue light.

4 **Predict** if diffraction would occur if light with a wavelength of 1×10^{-7} m struck a slit of width 1 mm. **Justify** your prediction.

Investigate, evaluate and communicate

5 Using the image of single slit diffraction in Figure 2, **propose** evidence to demonstrate that the greater the wavelength, the greater the diffraction.

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» Increase your knowledge
Finger fringes

» Increase your knowledge
Soap bubbles

» Weblink
Christmas beetles

SCIENCE AS A HUMAN ENDEAVOUR

16.9 Michelson–Morley experiment

KEY IDEAS

In this section, you will learn about:

+ uses of constructive and destructive interference.

An early use of interference principles in a scientific experiment was in 1887 when American scientists A. A. Michelson (1852–1931) and E. W. Morley (1838–1923) measured the speed of light into two directions (north–south, and east–west) at right angles.

They were concerned that there was no experimental proof of the *luminiferous aether*, which was supposed to be the absolute frame of reference for light. They argued that as Earth moves around the Sun, it should be moving through an *aether* or 'wind'. If there was an aether, and a beam of light was shone in the same direction as Earth's movement through it, the velocity of light would be measured as greater compared to light travelling at right angles to the direction of motion of Earth through the aether. Similarly, if light was shone in the opposite direction to Earth's movement through the aether, the velocity should be measured as smaller. That seemed logical.

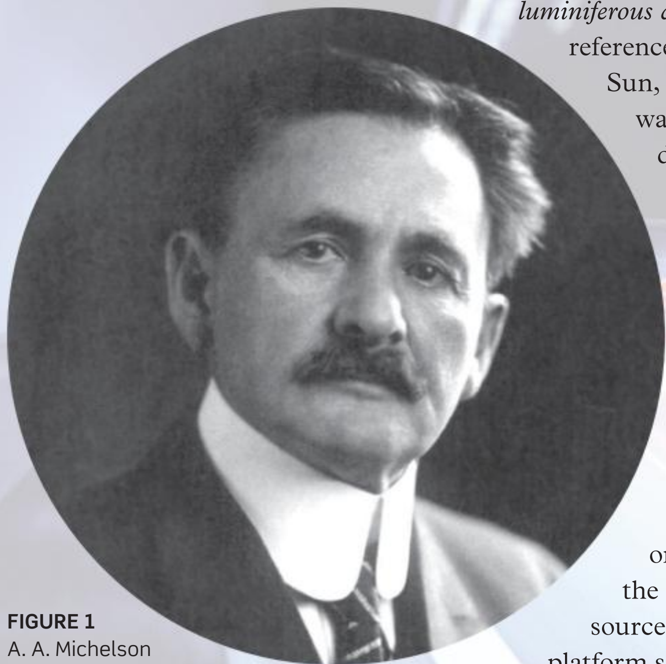

FIGURE 1 A. A. Michelson refuted the aether theory.

However, light travels so rapidly that direct measurement of its speed was not possible at the time. They were able to use an interferometer to measure the difference in the speed of light travelling with, against or across the aether. Figure 2 shows the path diagram for the interferometer. It was a huge instrument consisting of a source of coherent (single-wavelength) light and mirrors on a platform screwed to a massive granite stone block, floating in a pool of mercury so that it could be rotated.

Light was shone at a beam splitter that directed the light into two paths at right angles to each other (such as one beam going north and the other east). The two beams were reflected back to a screen and allowed to interfere. If there was any difference in their speed going north–south compared to going east–west, then there would be a 'fringe' shift as the granite slab was rotated. They tried everything – they rotated it left and right; they did the experiment in morning and afternoon, in summer and in winter, yet there was no fringe shift.

Trying to explain this 'null' result was going to be difficult for physicists. Some suggested that the aether was really there but it was at rest with respect to Earth because it was dragged along with Earth, and in this case the fringe shift would be zero. This was quickly dismissed as fanciful nonsense after some experiments with high-flying balloons were undertaken.

All theories attempting to explain the Michelson–Morley 'null' result were eventually replaced by the comprehensive theory proposed by Albert Einstein in 1905 – the special theory of relativity. Einstein was only eight years old when Michelson and Morley carried out their famous 1887 experiment.

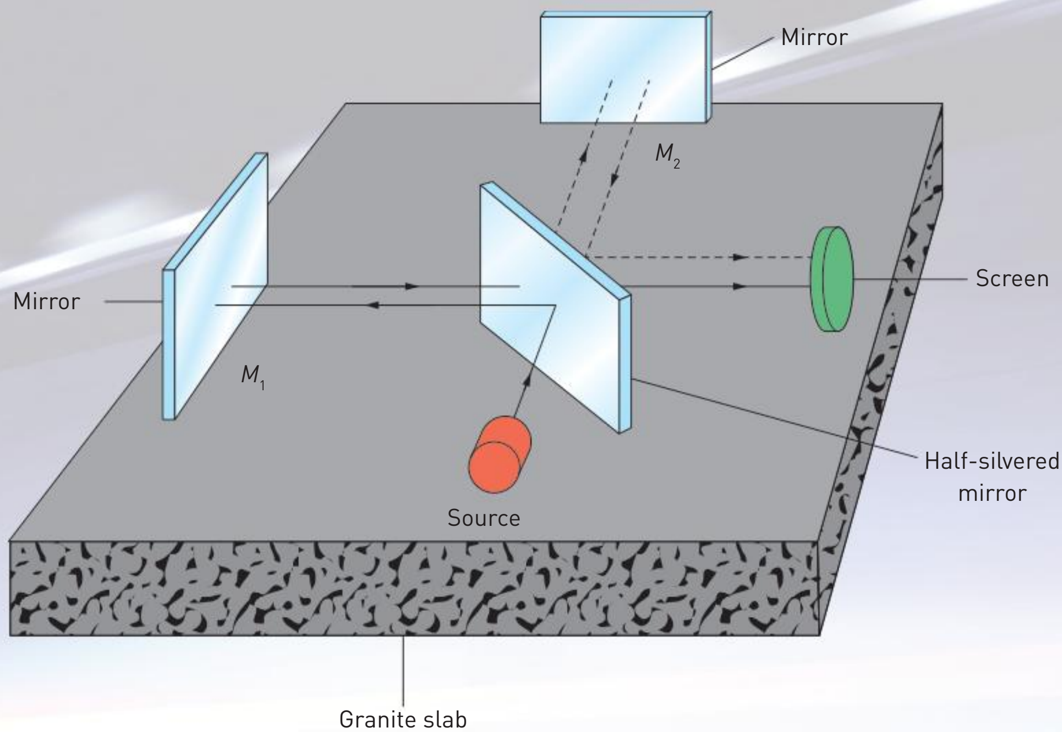

FIGURE 2 Light path in the Michelson–Morley experiment

CHECK YOUR LEARNING 16.9

Describe and explain

1 **Explain** the purpose of the Michelson–Morley experiment, and state whether their aim was achieved.

2 **Explain** why Michelson and Morley use 'coherent' light for the experiment. In your response, explain the meaning of the term.

3 When the waves from the two different light paths were out of phase, **explain** if Michelson and Morley got constructive or destructive interference. In your response, use the word 'fringes'.

Apply, analyse and interpret

4 The interferometer used yellow light with a frequency of 5.09×10^{14} Hz. The light was sent along a path length of 11.0 m from light source to detector.

a **Calculate** the wavelength of the light.

b **Determine** how many wavelengths fit into the 11.0 m path length.

Investigate, evaluate and communicate

5 Today, scientists searching for evidence of gravitational waves rely on a similar interferometer. However, gravitational waves make one arm of the interferometer stretch and the other shrink. **Propose** how this would affect the interference pattern of the two light waves on the screen.

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Science as a Human Endeavour: Interference of light

» **Weblink**
Michelson-Morley

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Michelson-Morley experiment

CHAPTER 16

Review

Summary

16.1
- Light is a form of electromagnetic energy that does not require a medium for its propagation. It is not a mechanical wave because it can travel through a vacuum.
- Light can be shown to exhibit properties that are characteristic of waves such as reflection, refraction, total internal reflection, dispersion, diffraction and interference.

16.2
- The electromagnetic spectrum consists of radio waves, microwaves, infra-red waves, visible light, ultraviolet waves, X-rays and gamma rays.
- Light exhibits polarisation – the ability to block some of the components of the electric and magnetic fields of electromagnetic radiation, in particular, visible light. A polariser is a device that is able to do this.
- Light polarisation can be explained using a transverse wave model.

16.3
- Intensity is proportional to the square of the amplitude.
- The intensity of light has an inverse-square relationship with the distance from the source.
- Diffraction is a phenomenon in which waves either bend behind a barrier or the wavefront is broken up into many small sources.
- Diffraction fringes can be produced by shining light through a single slit onto a screen.
- Diffraction increases with a decrease of slit (aperture) size and increase in wavelength.
- Interference is the combination of two or more waves to form a resultant wave. It can be constructive or destructive interference.

16.4
- When light reflects from a plane mirror, the angle of incidence equals the angle of reflection. The incident ray, the reflected ray and the normal all lie in the same plane.
- The image of an object in a plane mirror lies the same distance behind the mirror as the object is in front. The image is upright, the same size, virtual and laterally inverted.

16.5
- Refraction is the bending of light as it travels from one medium to another.
- Light travels at a slower speed in a more optically dense medium.
- Snell's law states that when light travels from one medium to another, the ratio of the sine of the angle of incidence to the sine of the angle of refraction is equal to the refractive index n; $\frac{\sin i}{\sin r} = n$.
- The ratio of the speed of light in two media is equal to the relative refractive index of the media; $n_{1\to2} = \frac{v_1}{v_2}$.
- The absolute refractive index is obtained when light travels from air to another medium.
- The relative refractive index is obtained when light passes from one medium to another and is given by the formula $n_{1\to2} = \frac{n_2}{n_1}$.
- In general, for light passing from medium 1 to medium 2, $n_1 \sin\theta_1 = n_2 \sin\theta_2$. Also $n_{1\to2} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1}$.

16.6
- Total internal reflection occurs when light is shone at an angle greater than the critical angle from a more optically dense to a less optically dense medium.
- The critical angle is the angle of incidence in a material that produces an angle of refraction of 90° in air (or the less dense medium).
- For total internal reflection, $\sin\theta_c = \frac{1}{n}$ where θ_c is the critical angle and n is the relative refractive index.

- The speed of light is 3×10^8 m s^{-1} in a vacuum and less in other media.

16.7
- Lenses come in many shapes and sizes, but the most commonly used are convex (converging) and concave (diverging) lenses.
- Lenses refract light toward the thickest part of the lens.
- Convex lenses converge light rays that are parallel to the principal axis to the focal point.
- Concave lenses diverge light rays that are parallel to the principal axis so as they appear to come from the principal focal on the same side of the lens as the object.

16.8
- Images in lenses can be described using the terms real or virtual, upright or inverted, and smaller or larger.
- Convex lenses produce real, inverted images when the object is outside the principal focus, and virtual, upright images when the object is inside the principal focus.
- Concave lenses always produce virtual, upright and smaller images.
- The focal length of convex lenses can be found by focusing parallel light rays either from a light box or from a distant object onto a screen.

Key terms

- absolute refractive index
- critical angle
- centre of curvature
- converging
- converging lens
- diffraction
- dispersion
- diverges
- diverging lens
- electromagnetic wave
- focal length
- intensity
- interference
- particle model of light
- principal axis
- principal focus
- polarisation (linear)
- polariser
- real image
- reciprocal law
- rectilinear propagation
- reflection
- refraction
- Snell's law
- spectrum
- total internal reflection
- virtual image
- wave model of light

Key formulas

Refraction	$\frac{\sin i}{\sin r} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1}$
Intensity and distance	$I \propto \frac{1}{r^2}$
Critical angle	$\sin\theta_c = \frac{1}{n}$

Revision questions

The relative difficulty of these questions is indicated by the number of stars beside each question number: * = low; ** = medium; *** = high.

Multiple-choice

1 The diagram in Figure 1 represents an electromagnetic wave that is undergoing:

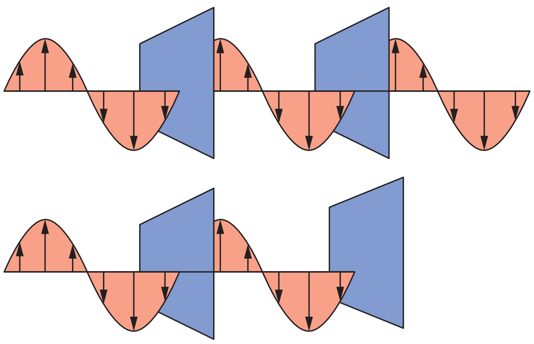


FIGURE 1 Electromagnetic wave

A polarisation
B diffraction
C dispersion
D interference

2 The diagram in Figure 2 shows light as it passes between medium I and medium II. If the absolute refractive index of medium II is 1.33, the possible refractive index of medium I is:

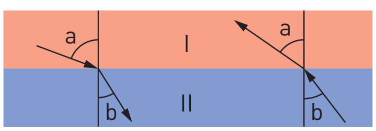


FIGURE 2 Light passing between medium I and II

A 0.9
B 1.0
C 1.33
D 1.5

3 When light strikes substance X (from air) at an angle of incidence of 40° the angle of refraction is measured at 29°. When light strikes substance Y (from air) at an angle of 40°, the angle of refraction is measured at 34°. Which one of the following is closest to the angle of refraction when light strikes substance X (from substance Y) at an angle of incidence of 40°?

A 5°
B 63°
C 67°
D 85°

4 An object 4.0 cm high is located 15 cm in front of a plane mirror. Which one of the following best describes the characteristics and the location of the image?

A virtual, 4 cm high, upright, 15 cm behind the mirror
B virtual, 4 cm high, inverted, 15 cm behind the mirror
C real, 4 cm high, upright, 15 cm behind the mirror
D real, <4 cm high, upright, <15 cm behind the mirror

5 The critical angle for a beam of light striking the interface between a certain type of glass and air is 41°. If the glass was placed in a liquid medium with an absolute refractive index of 1.3, which one of the following best states the new critical angle?

A <41°
B 41°
C >41°
D 90°

Short answer

Describe and explain

★ 6 **Identify** two properties of waves that are considered to be strictly wave characteristics.

★ 7 **Recall** if there is any one model for light that can explain all of its properties.

★ 8 **Recall** the angle between the electric and magnetic wave planes in polarised light.

★ 9 When a light ray goes from a less optically dense medium to a more optically dense medium, does the ray bend toward or away from the normal? **Sketch** a diagram to show your answer and propose two media that would demonstrate this.

★ 10 **Recall** Snell's law and describe the meaning of the terms.

★ 11 **Recall** the meaning of 'dispersion' and explain what characteristic of light makes it happen.

★ 12 a **Sketch** ray diagrams for a convex lens showing the images produced when an object is placed at:

i >2*f*
ii 2*f*
iii between F and 2*f*
iv F
v <*F*.

b **Sketch** a similar ray diagram for a concave lens where the object is at 2*f*.

★ 13 **Recall** the definition of 'diffraction' and give an example of this phenomenon.

★ **14** A light source has an intensity of 20 W m^{-2} at a distance of 100 m from a source. **Calculate** its intensity at:

a 200 m

b 1.0 km.

★ **15** A beam of light is incident on water (n_{water} = 1.33) at an angle of incidence of 35.0°.

a **Calculate** the angle of refraction.

b **Calculate** the angle the refracted ray makes with the surface of the water.

★ **16** A small light 4.0 cm high is placed 25.0 cm in front of a concave lens of 10.0 cm focal length. **Sketch** a ray diagram to find:

a the position of the image

b the height of the image.

★ **17** A candle 3.0 cm high is placed 5.0 cm in front of a convex lens of 20 cm focal length.

a **Sketch** a ray diagram to find the image.

b **Describe** the nature of the image and **calculate** its magnification.

★★ **18** A light ray strikes the surface of a block of fused quartz at an angle of 54° to the normal.

a **Calculate** the angle of refraction.

b **Calculate** the velocity of light in the quartz.

★★ **19** **Calculate** the absolute refractive index for light going from air to a medium when the velocity of light in the medium is:

a 2.4×10^8 m s^{-1}

b 1.8×10^8 m s^{-1}.

★★ **20** The refractive indices of flint glass and turpentine are 1.65 and 1.5 respectively.

a **Calculate** the refractive index for light passing from turpentine to flint glass.

b If the angle of incidence in the turpentine is 49°, **calculate** the angle of refraction in the flint glass.

★★ **21** In each of the following cases, **sketch** a ray diagram to find the position and characteristics of the image.

a A 2.0 cm high object is placed 10 cm in front of a 20 cm focal length convex lens.

b A 5.0 cm object is placed 18 cm in front of a 6.0 cm focal length concave lens.

c A 10 cm high object is placed 50 cm in front of a 25 cm focal length convex lens.

Apply, analyse and interpret

★ **22** **Determine** the value of the refracted angle when the incident ray of light is at the critical angle.

★ **23** **a** Using $v = f\lambda$, **calculate** the speed in air of:

i red light of wavelength 620 nm

ii blue light of wavelength 470 nm

iii X-rays of wavelength 1.0 nm.

b **Calculate** the frequency of each of the above electromagnetic waves.

c **Determine** the frequency of each of the above rays in water. (n_w = 1.33)

★ **24** For each of the following situations where a light ray passes from one medium to another, **determine** whether the light ray will bend away from or toward the normal. Use Table 1 on page 446 to find values to help you decide.

a air to water

b glass to air

c water to glass

d diamond to glass

e flint glass to crown glass

f perspex to a vacuum

★ **25** Given the absolute refractive indices of n_{air} = 1.00, n_{water} = 1.33 and n_{glass} = 1.52, **determine** for each which way light will bend (towards the normal or away from the normal), briefly justifying your decision:

a air to glass

b glass to air.

★ **26** 'Total internal reflection always occurs when a light beam in a more dense medium strikes a boundary to a less dense medium.' **Clarify** whether this statement is accurate or not.

★ **27** A wavefront approaches a fixed barrier at an angle of 30° to the barrier. **Determine**:

a the angle of incidence

b **Create** a labelled diagram to show these angles

c the angle of reflection.

d the angle the direction of propagation makes with the barrier.

★★ **28** A light source has an intensity of 150 W m^{-2} at a distance of 100 m from a source. **Determine** how far from the source its intensity would be 100 W m^{-2}.

★★ **29** Light from a light box is directed at an angle of 30° onto a block of glass whose refractive index is 1.5, and then onto the surface of salty water whose refractive index is 1.4. **Determine** in which case the light will bend the most.

★★ **30** The absolute refractive indices of certain media are:

i 1.78
ii 1.2
iii 2.1
iv 1.42.

a **Calculate** the speed of light in each of the media.

b **Determine** which substance is the most optically dense.

★★ **31** In each of the four cases shown in Figure 3, a light ray travels from air to the substance. Use the diagrams to determine the refractive index of the substances.

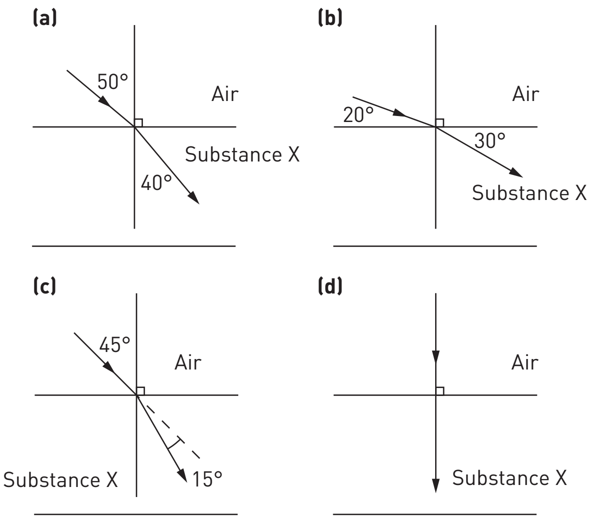


FIGURE 3 Ray diagrams

★★★ **32** The index of refraction for glass is different for different colours of light. The refractive index for blue light (λ = 430 nm) passing from air into flint glass is 1.650 and for red light (λ = 680 nm) is 1.615. A beam containing blue and red light is shone onto a block of flint glass at an angle of 52°. **Determine** the angle between the blue and the red rays in the glass.

★★★ **33** **Consider** the following optical fibre cable. The initial feed-in of light occurs from air into the core material (Figure 4).

A design engineer claims that a feed-in angle of 40° would allow total internal reflection to occur.

a **Determine** whether the engineer is correct. Support your argument through quantitative analysis.

b Regardless of whether you supported the engineer or not, **determine** what range of feed-in angles would allow total internal reflection to occur.

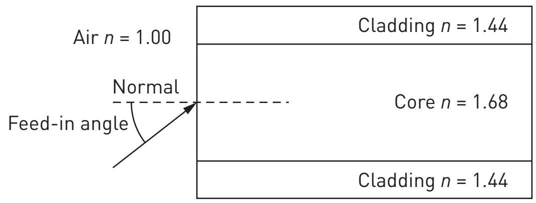


FIGURE 4 Optical fibre cable

★★★ **34** An object 5.0 cm high is placed 1.8 m in front of a convex lens. An image 6.8 cm high is produced on a screen. Use a ray diagram to **determine** the focal length of the lens.

★★★ **35** A beam of white light is shone onto a glass prism such that the angle with the second surface is the critical angle for yellow light (Figure 5). **Analyse** what occurs to the beam of white light.

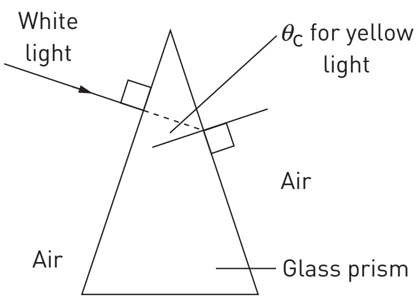
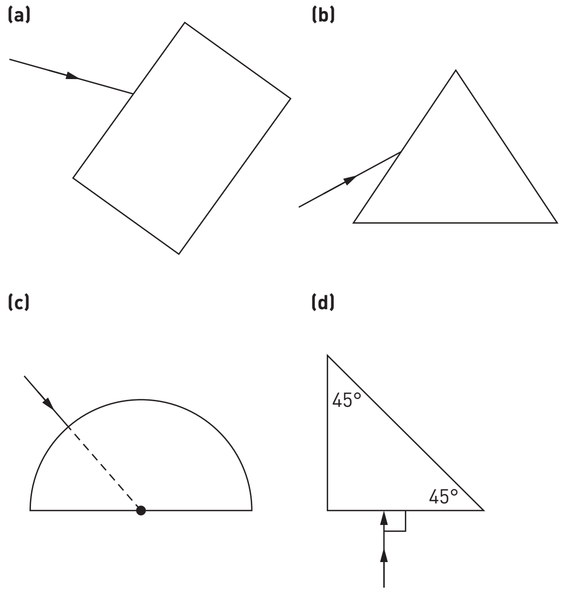


FIGURE 5 Beam of white light shone onto a glass prism

Investigate, evaluate and communicate

★ **36** If the distance to a light source is doubled, **predict** what happens to its intensity.

★★ **37** **Predict** the path of light in each of the diagrams shown in Figure 6, where a ray of light passes from air to a block of glass.



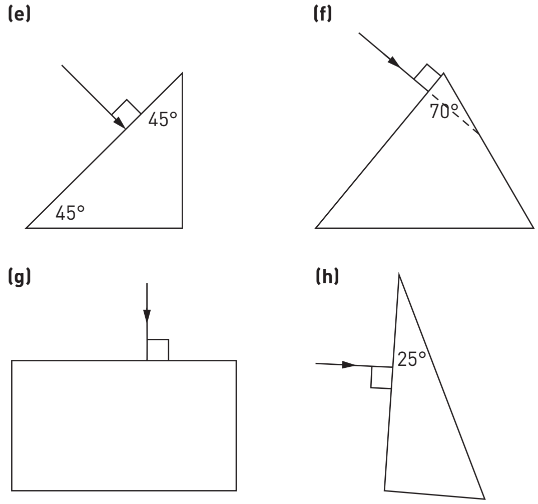


FIGURE 6 Light ray passing from air to a block of glass

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UNIT 2

Practice exam questions

Linear motion and waves

Multiple-choice

1 The diagram in Figure 1 shows the horizontal force vectors acting on a collision trolley. Which of the following is most likely to be true about this situation?

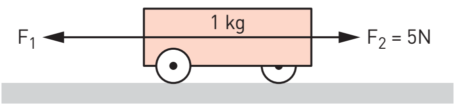


FIGURE 1 Horizontal force vectors acting on a collision trolley

A The trolley is accelerating at 5 m s^{-2} to the left.

B The trolley is accelerating at 10 m s^{-2} to the left.

C F_1 could be the frictional force.

D The vector sum of the forces is 15 N.

2 The graph in Figure 2 shows the motion of a dog.

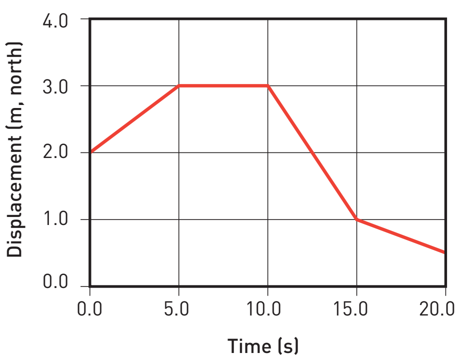


FIGURE 2 Motion graph of a dog

During which interval does the dog have the fastest velocity?

A 0.0–5.0 s
B 5.0–10.0 s
C 10.0–15.0 s
D 15.0–20.0 s

3 A ball tossed vertically upward rises, reaches its highest point and then falls back to its starting point. During this time the acceleration of the ball is always:

A in the direction of motion.

B opposite its velocity.

C directed downward.

D directed upward.

4 A boy pulls a 50 kg crate horizontally with a force of 450 N and the friction force on the crate is 250 N. The acceleration of the crate is:

A 2 m s^{-2}
B 4 m s^{-2}
C 9 m s^{-2}
D 14 m s^{-2}

5 A ball is projected into the air with 200 J of kinetic energy that is transformed to gravitational potential energy at the top of its trajectory. When it returns to its original level after encountering air resistance, its kinetic energy is:

A 0 J.

B less than 200 J but not 0 J.

C more than 200 J.

D 200 J.

Short answer

6 A car starts from rest and reaches a velocity of 15 m s^{-1} in 5 seconds. Calculate how far the car travelled in this time.

7 Calculate the magnitude of the momentum of the following moving objects:

a 1.5 tonne car moving at 15 m s^{-1} (1 tonne = 1000 kg)

b Earth in its journey around the Sun (Earth's mass is 6×10^{24} kg and its average radius of orbit is 1.5×10^{11} m)

8 Students experimenting with an unknown transparent substance used a light box to produce a ray of light. They shone the ray onto the unknown substance at various angles and measured the angles of refraction. Use their results in Table 1 to find the refractive index of the substance.

TABLE 1

Angle of incidence, *i* (degrees)	30	40	50
Angle of refraction, *r* (degrees)	14	20	24

Combination response

9 A ball is thrown vertically upward at 30 m s^{-1}. Calculate:

a its maximum height

b the time taken to reach this height

c time of flight.

10 Two blocks of masses 2 kg (A) and 4 kg (B) respectively rest on a smooth horizontal surface and are connected by a taut string of negligible mass. A force of 18 N is applied to the 4 kg mass as shown in Figure 3. Calculate:

a the tension in the string between the blocks

b the acceleration of the system.

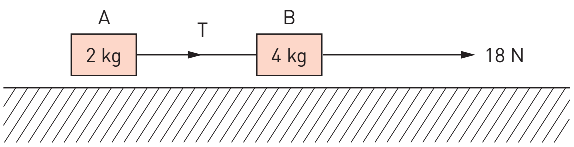


FIGURE 3 Two blocks connected by a taut string

11 A standing wave is made to form in a closed pipe and vibrates at the fifth harmonic.

a Sketch a diagram showing displacement of the air particles in the standing wave.

b Label the diagram to indicate the displacement nodes.

c If the velocity of sound in air was 345 m s^{-1} and the frequency of the sound was 440 Hz, calculate the length of the pipe.

12 A car of 1500 kg travelling at 30 m s^{-1} collides into the rear of another car of 2000 kg travelling at 20 m s^{-1} in the same direction. The collision is great enough that the two cars stick together after they collide. The cars roll freely and it is assumed that there is no friction with the road.

a Predict, with reasons, how fast both cars will be going after the collision.

b Explain whether momentum is conserved in this collision.

c Deduce whether kinetic energy is conserved in this collision. Support your statement with a reasoned mathematical explanation.

13 A vertical tube 1.0 m in length is filled with water. The water is slowly let out by a tap at the bottom of the tube while a tuning fork of frequency 512.0 Hz is sounded and held over the top of the tube. (Note: the speed of sound in air is 340.0 m s^{-1}.)

Considering an observer is solely interested in any resonance (loud) sound coming from the tube due to the vibration of the tuning fork, determine and explain what the observer will hear from the time the tube starts to empty until it is empty of water. Use both calculations and diagrams to support your explanation.

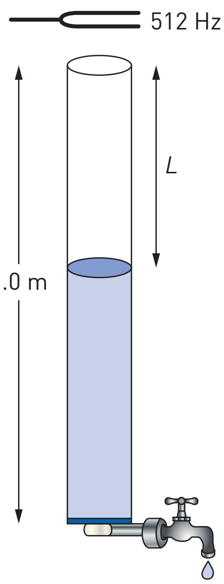


FIGURE 4 A tuning fork is sounded over the top of the tube filled with water as it is being emptied.

14 An optical fibre consists of a core made of glass of refractive index $n_1 = 1.5$. It is through this core that light travels along the fibre. The core is surrounded by another layer of glass of lower refractive index n_2, which is called the 'cladding'.

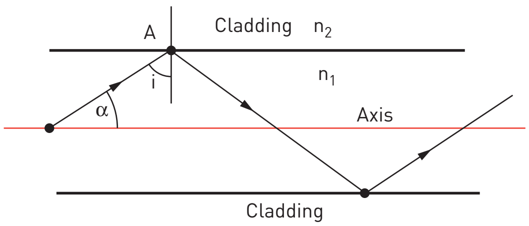


FIGURE 5 Light travelling along an optical fibre

a Evaluate this arrangement and deduce what the refractive index n_2 of the cladding needs to be so that the critical angle at the interface core cladding is 80°.

b α is the angle made by the ray with the axis of the fibre. For what values of α is the incident angle *i* larger that the critical angle found in part (a)? Justify your statement by reasoned mathematical argument.

CHAPTER 17

Practical manual

This chapter is a guide to all of the mandatory practicals included in the QCAA Senior Physics Syllabus. Please refer to your obook assess for access to the suggested practicals from the syllabus. These practicals are not prescriptive and schools may adapt the practicals to their resources.

The practicals in this chapter have been trialed, and safety instructions are provided; however, it is the legal obligation of the teacher to perform their own risk assessments prior to participating in any practical activity.

Chapter 0, The Physics Toolkit, is a good reference for completing data collection and analysis for any practical you encounter in your senior physics course.

While completing this chapter safety hazards will be highlighted at the top of each practical; when undertaking practical experiments you should always wear lab coats, safety glasses, have enclosed footwear and long hair tied back. Below is a summary of general safety cautions:

→ Burns – hot water and hotplates can cause burns in the lab. These can be avoided by not moving boiling water and avoiding splashing, as well as leaving heated samples to cool before using them. It is also important to ensure that each member of your group is aware that a hotplate is on, and once you have finished with it, use a hazard sign to warn others that it may still be hot.

→ Electrical cords – always keep electrical cords away from water and hot metal surfaces.

→ Electric shock – Electrical equipment can cause electric shocks, and cause serious or fatal injury. When using electrical equipment make sure that there are no exposed wires.

→ Glass – glass can shatter and cut you. Be careful when you are using thermometers, conical flasks, beakers or other glassware in the lab. Make sure you handle each item with care. Do not use your hands to pick up broken glass.

→ Ionising radiation – exposure to ionising radiation can be extremely dangerous. You should have a risk management plan in place suitable for use with radioactive sources. This plan could include Queensland Health's *Radioactive Substances used for Science Activities* and *The Radiation Protection Series* published by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA). The following control measures can also be used; using only very low-activity radioactive sources of americium-241 (max. 10 kBq), strontium-90 (max. 10 kBq) and cobalt-60 (max. 100 kBq). You should also use sealed radioactive sources, reduce the time of exposure, maintain a distance from the source, increase shielding between the user and the source, or you can conduct a simulation.

→ In the event that an injury or accident does happen make sure you tell your teacher immediately.

You should also complete **risk assessments** before you conduct any practical. Please familiarise yourself with your school's safety procedures including the location of first aid kits, safety equipment, chemical waste disposal, and the set-up and pack-down of practical stations. If you are unsure of any steps in any practical you should check with your teacher for the best course of action.

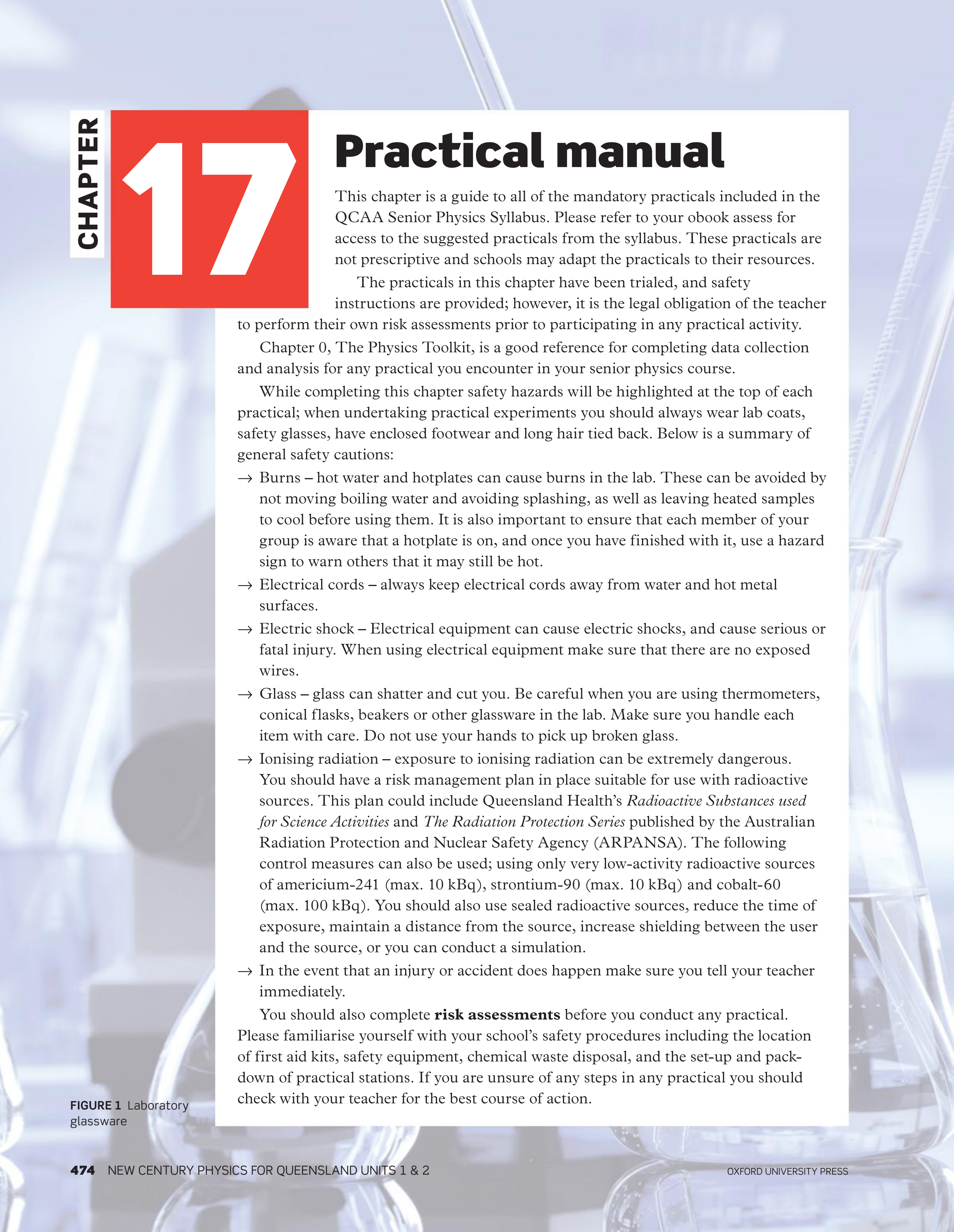


FIGURE 1 Laboratory glassware

UNIT 1 PRACTICALS

MANDATORY PRACTICAL	**1.1** Heating water on a hotplate – graphing and analysing data
MANDATORY PRACTICAL	**2.2** Specific heat of a metal – by calorimetry
MANDATORY PRACTICAL	**8.1** Finding resistance of an ohmic resistor
SUGGESTED PRACTICAL	**1.2** Precision and accuracy of thermometers
SUGGESTED PRACTICAL	**2.3** Calorimetry – method of mixtures
SUGGESTED PRACTICAL	**2.4** Observations of phase change – during heating
SUGGESTED PRACTICAL	**5.1** Shielding effects from a radioactive source
SUGGESTED PRACTICAL	**5.2** Relationship between activity and distance from a radioactive source
SUGGESTED PRACTICAL	**8.2** Ohmic and non-ohmic devices
SUGGESTED PRACTICAL	**9.1** Investigating series and parallel circuits
SUGGESTED PRACTICAL	**9.2** Circuits for real life purposes – using a fuse for protection

UNIT 2 PRACTICALS

MANDATORY PRACTICAL	**10.1** Acceleration due to gravity on Earth's surface
MANDATORY PRACTICAL	**10.2** Constructing and interpreting displacement-time and velocity-time graphs
MANDATORY PRACTICAL	**16.1** Refractive index of a transparent substance
SUGGESTED PRACTICAL	**12.1** Elastic collision between trolleys – momentum conservation
SUGGESTED PRACTICAL	**14.1** Longitudinal and transverse waves on springs
SUGGESTED PRACTICAL	**15.1** Investigating fundamental and harmonic wavelengths in pipes
SUGGESTED PRACTICAL	**15.2** Speed of sound in air using a closed-end pipe over water
SUGGESTED PRACTICAL	**16.2** Verifying the law of reflection – images in a plane mirror

1.1 MANDATORY PRACTICAL

Heating water on a hotplate – graphing and analysing data

CAUTION: HOT WATER CAN CAUSE BURNS.
HOTPLATES CAN CAUSE BURNS.
ELECTRICAL EQUIPMENT CAN CAUSE ELECTRIC SHOCKS.

Unit 1, Topic 1: Conduct an experiment that obtains data to be plotted on a scatter graph (with correct title and symbols, units and labels on the axes), analysed by calculating the equation of a linear trend line, interpreted to draw a conclusion, and reported on using scientific conventions and language.

Source: *Physics 2019 v1.2 General Senior Syllabus Queensland Curriculum & Assessment Authority*

Context

When you heat tap water, its temperature rises – but does doubling the amount of water lead to half the temperature rise? If 100 mL of water is heated for 2 minutes, will its temperature rise be twice that for heating 200 mL for the same time?

Aim

To investigate whether there is a proportional relationship between heat and temperature change.

Materials

- 100 mL measuring cylinder
- Thermometers (alcohol-in-glass, 0–110°C)
- Data-logger and temperature probe (optional)
- Laboratory hotplate
- 2 × 250 mL glass beakers
- Timer
- Water

Method

1. Read the method and prepare a data table for the results.
2. Turn a hotplate onto 'high' and leave it for a few minutes to reach its maximum temperature.
3. Place 100 mL tap water and 200 mL tap water in similar shaped 250 mL beakers and take their temperatures.
4. Place the beakers on the hotplate with care and take temperature readings every 30 seconds for 4 minutes.
5. Turn the hotplate off once the temperature rises above 80°C.
6. Place caution sign in front of hotplate to warn others.

Results

1. Plot the heating curves for each sample on the same graph (time should be on the horizontal axis and temperature on the vertical axis).
2. Draw a linear line of best fit and determine the equation for the line, and its R^2 value.

Discussion

1 Interpret the graphs to specify whether the rate of temperature rise is uniform for each sample (that is, is the heating curve a straight line)? Account for your statement.

2 Deduce what the linear shape tells you about the relationship between heat added and temperature rise.

3 The slope of each graph is its heating rate (as denoted by the '*m*' term in the equation for the line $y = mx + c$). Use the value for the slope to compare the heating rates of the 100 mL sample and the 200 mL sample.

4 Compare the rise in temperature for both samples. After 2 minutes, did the 100 mL sample rise in temperature twice as much as the 200 mL? What can you conclude about the temperature rise of different volumes of water?

5 Examine the design of the experiment to identify whether all the heat is going into the water. If you have said it is not, propose where it may be going.

6 Outline how you could modify the experiment to reduce errors, and state why these modifications would work.

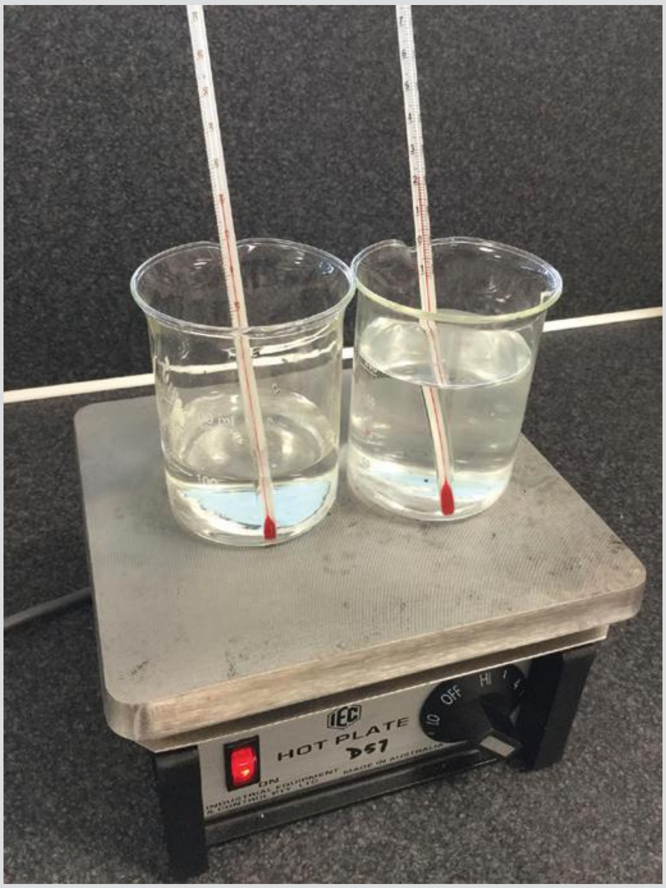


FIGURE 1 Set-up for experiment

2.2 MANDATORY PRACTICAL

Specific heat of a metal – by calorimetry

CAUTION: BOILING WATER CAN CAUSE BURNS.
HOT SUBSTANCES CAN CAUSE BURNS.
HANDLE THESE WITH CARE.

Unit 1, Topic 1: Conduct an experiment that determines the specific heat capacity of a substance, ensuring that measurement uncertainties associated with mass and temperature are propagated. Where the mean is calculated (in this, and future experiments), determine the percentage and/or absolute uncertainty of the mean.

Source: *Physics 2019 v1.2 General Senior Syllabus Queensland Curriculum & Assessment Authority*

Context

Knowing the specific heat capacity of water allows us to determine the specific heat capacity of other substances by using the method of mixtures. In this experiment, a piece of hot metal will be used to warm up some cool water and the changes in temperature noted.

Aim

To determine the specific heat capacity of a metal.

Materials

- 2 × 50 g brass masses
- 250 mL glass beaker
- 100 mL measuring cylinder
- 20 cm cotton thread
- 200 mL foam cup
- Tongs (metal)
- Hotplate or Bunsen burner/tripod/gauze mat/ heatproof mat
- Thermometer (–10–110°C)
- Tap water

Method

1. Place 100 mL tap water in the 250 mL beaker and place on a hotplate.
2. Tie the piece of cotton thread securely around the brass masses so they can be lifted by the thread.
3. Place the masses in the beaker and allow a small amount of the thread to hang over the side of the beaker.
4. Heat the water to boiling.
5. Accurately measure out 50 mL (or 50 g) of tap water into a foam cup and record its temperature. Leave the thermometer in the cup.
6. When the water in the beaker has boiled, pick up the end of the thread with metal tongs and hold it steady until the water just finishes evaporating off the mass.
7. Transfer the brass masses into the water in the foam cup. Do this as quickly as possible without splashing.
8. Stir the water gently with the thermometer until the temperature remains the same for consecutive readings. Note the temperature.
9. Place caution sign on hotplate to warn others of heat.

Results

TABLE 1 Result table

Initial				Final
m (brass)	T^i (brass)	*m* (water)	T^i (water)	T^f (water)
± g	100.0 ± °C	± g	± °C	± °C

Precision

1 Calculate the specific heat capacity of the metal.

2 Calculate the absolute uncertainty of the specific heat capacity by determining the measurement uncertainty associated with mass and temperature.

3 Calculate the percentage uncertainty of the mean.

Accuracy

4 Find the accepted value for the specific heat capacity of the metal you used, and hence calculate the absolute and percentage errors.

Discussion

1 The method said to transfer the hot metal to the foam cup as quickly as possible. Deduce the purpose of this instruction.

2 You were also instructed to wait for the water to evaporate off the metal before transferring it to the foam cup. Predict the effect of allowing water to remain on the metal when it is being transferred.

3 Account for the sources of error in your experiment and propose how they can be reduced. Nominate whether they are systematic or random errors.

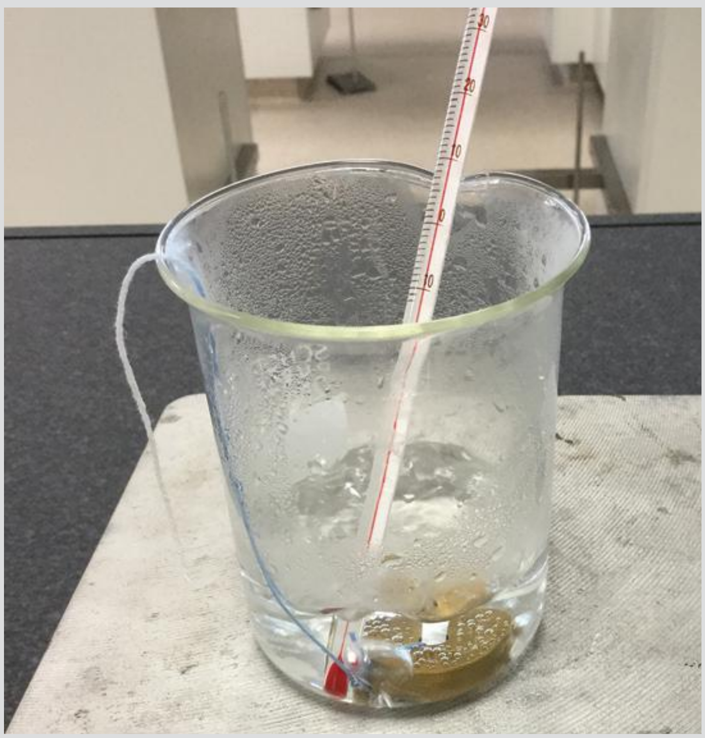


FIGURE 1 Care is needed when removing the metal from boiling water.

8.1 MANDATORY PRACTICAL

Finding resistance of ohmic resistor

CAUTION: ELECTRICAL EQUIPMENT CAN CAUSE ELECTRIC SHOCKS.

Unit 1, Topic 3: Conduct an experiment that measures electric current through, and electrical potential difference across, an ohmic resistor in order to find resistance.

Source: *Physics 2019 v1.2 General Senior Syllabus Queensland Curriculum & Assessment Authority*

Context

The relationship between current through an ohmic resistor and the potential difference across it can be used to find the resistance. This relies on a relationship known as Ohm's law.

Aim

To determine the resistance of an ohmic resistor by investigating the relationship between current and potential difference.

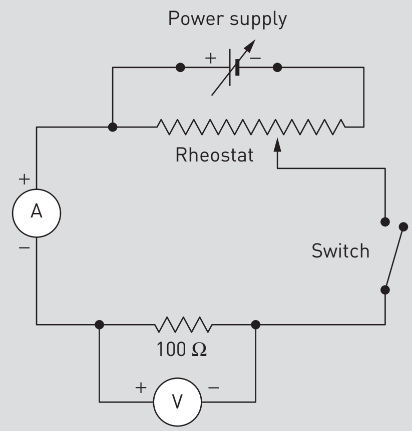
Materials

- Power supply 0–12 V DC
- Ammeter
- Voltmeter
- Fixed resistor (100 to 470 Ω is suitable)
- Rheostat
- Connecting wires

Method

1. Set up the circuit shown in Figure 1 using the DC output of the laboratory power supply.
2. Connect the wires to the meters using the highest voltage and current scales possible.
3. Connect in a fixed resistor, *R*. A resistance up to 470 Ω is suitable.
4. Adjust the rheostat so that the slider is close to the positive side. This will ensure a small voltage is delivered (impressed) across the resistor.
5. Adjust the power supply to the 6 V setting, close the switch and adjust the rheostat so that 1.0 V appears on the voltmeter. Take readings for the voltage and current and quickly release the switch so it returns to the open (off) position. This will reduce the risk of overheating. If necessary, adjust the scales on either meter to a more sensitive range. If the needle goes off the scale (or to a 1 on a digital scale), open the switch immediately.
6. Adjust the position of the slider on the rheostat to get approximately 2.0 V on the voltmeter. Record the voltage and current.
7. Keep adjusting the rheostat and taking pairs of *V* and *I* data until five pairs have been recorded.

(a)



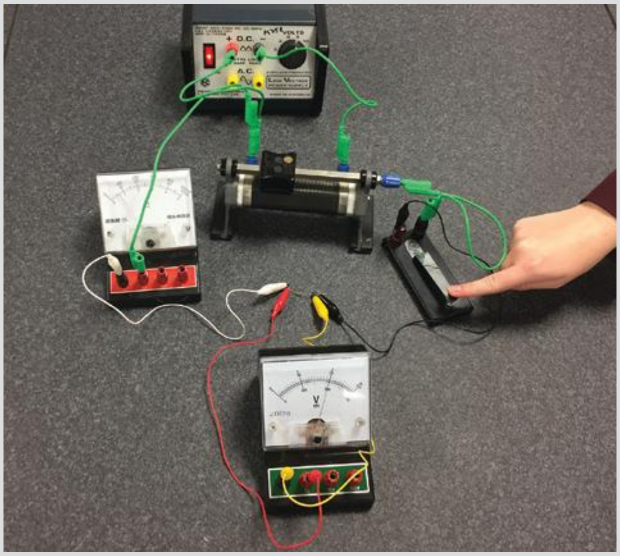


FIGURE 1 (a) Circuit diagram and (b) equipment set-up for the experiment

Results

TABLE 1 Results table

Voltage, *V*		Current I (*A*)			
(V)	Uncertainty, δ (± V)	Test 1	Test 2	Mean	Uncertainty, δ
1.0					
2.0					
3.0					
4.0					
5.0					

1. For each reading, record the uncertainty as ± half-scale division for analogue (printed scale) meters or ± the smallest decimal place for a digital scale.
2. Analyse the experimental data by plotting *V* (x-axis) vs *I* (y-axis) using error bars to show the uncertainty of the measurements.
3. If using a spreadsheet, add a trendline, show the equation and display the R^2 value.
4. Identify any anomalies or outliers in the data.
5. Calculate the gradient of the line. If you have plotted voltage on the horizontal axis then calculate the reciprocal of slope to get a value for resistance. If you have plotted current on the horizontal axis then the slope is equal to the resistance.
6. Determine maximum and minimum trendline values from the graph. Determine the uncertainty in the values for resistance.
7. Identify the value of the resistors used in the experiment from a colour chart and use this information to calculate the absolute error and relative error.

Discussion

1. Comment on whether the resistor appears to be ohmic or non-ohmic.
2. Propose why the R^2 value is not equal to 1.00 (if it is not).
3. Comment on whether the graph shows evidence of random or systematic error.
4. Predict what would happen if the switch was left closed for too long and the resistor became very hot.
5. Critically evaluate the design and method used to examine the relationship between current and voltage in an ohmic conductor. Comment on strengths and weaknesses such as sources of error and limitations of the data.
6. Describe effective and relevant suggestions for the improvement of the experiment. For each suggestion describe:
   a. the change suggested
   b. why it is a problem
   c. how the change will address the problem.
7. Make a conclusion that is clearly justified and supported by the data.

10.1 MANDATORY PRACTICAL

Acceleration due to gravity on Earth's surface

CAUTION: AVOID STANDING ON CHAIRS AND TABLES FOR EXTRA HEIGHT.
BEWARE OF BEING STRUCK ON HEAD BY FALLING OBJECTS.

Unit 2, Topic 1: Conduct an experiment to verify the value of acceleration due to gravity on the Earth's surface. All data sets that suggest a non-linear relationship, data (e.g. t^2 versus s) should be linearised and plotted, allowing for the calculation of the equation of a linear trend line. An evaluation of the experimental process undertaken, and of the conclusions drawn, will require students to:

- discuss the reliability and validity of the experimental process with reference to the uncertainty and limitations of the data such as measurement uncertainty and percentage error
- identify justifiable sources of imprecision and inaccuracy
- suggest improvements or extensions to the experiment using the uncertainty and limitations identified

Source: *Physics 2019 v1.2 General Senior Syllabus Queensland Curriculum & Assessment Authority*

Context

Students are very familiar with measuring acceleration due to gravity by dropping a ball from a height. In this experiment they can use graphical analysis to measure the value more accurately and to identify systematic and random errors. Note that it is the intention of this practical to measure the time using a stopwatch. This will provide you with an opportunity to refine the design later for a Student Experiment, for example, using video analysis.

Aim

To verify the value of acceleration due to gravity on Earth's surface.

Materials

- Ball (eg cricket ball, ball bearing)
- Metre ruler, tape measure
- Stopwatch

Method

1. Decide on seven heights from which to drop a ball. The smallest should be no less than 40 cm, and the largest should be at least 5 to 10 times this. It is better to have the lesser heights closer together than the larger heights. This is because a graph will show a large curve at these smaller values (see sample data table).
2. Measure accurately a point on a wall at the first height for your independent variable. Mark this point without damaging the wall.
3. Hold a ball with its lower surface at the mark and drop it. Simultaneously start a timer, and stop the timer when the ball strikes the floor. Practise this a few times before recording data. You should decide on a method for starting and stopping the time to minimise error from reaction time.
4. Do three replicate tests at this height and record the data. Repeat this for the next trial height and so on until at least seven heights are tested.

5 The scale reading uncertainty for a stopwatch is ± the least significant decimal place (probably ± 0.01 s) but this is overshadowed by the much larger uncertainty due to human reaction time (± 0.1 to 0.2 s). Your recorded times could show this scale reading uncertainty but as you are doing replicates the formula for uncertainty from repeated measures will be used: $\delta = \pm\frac{(x_{max} - x_{min})}{2}$. Calculate the absolute uncertainty using this formula and enter it in the final column. As well, calculate the percentage uncertainty. This is a useful measure of the reliability of your experiment.

Results

TABLE 1 Results table

Displacement s, (m) ± 0.005 m	Time, t (s) ± 0.2 s				Uncertainty	
	Test 1	Test 2	Test 3	Average	Absolute ± δ (m)	Percentage ± δ%
0.40						
0.80						
1.20						
1.60						
2.00						

1 It is usual to plot the independent variable on the horizontal axis, but in this case, graphical analysis is simplified by plotting it on the vertical axis. Hence, plot a graph of the independent variable **displacement**, s (vertical axis) vs the dependent variable **time**, t (horizontal axis). It should appear to show the relationship: $y \propto x^2$. This is equivalent to $s \propto t^2$.

2 Add custom error bars to your data. There is insignificant uncertainty in the displacement data so no error bars for this quantity are needed. However, you should add horizontal error bars for the recorded times. These are the uncertainty values from your table.

3 The equation $s = ut + \frac{1}{2}at^2$ shows that the relationship between s and t is expected to be $s \propto t^2$ (a squared relationship) when the acceleration a (or g) due to gravity is constant and the starting speed u is zero. To confirm this you will need to linearise the graph by plotting t^2 on the horizontal axis and s on the vertical axis. First, calculate the time squared (t^2) values for each test you did at each displacement (drop height). Record this in a table. If you are computing this in a spreadsheet, extend your original data table.

4 Calculate the absolute uncertainty (δ) in the average value of t^2 using $\delta = \pm\frac{(x_{max} - x_{min})}{2}$ and add it to the table.

5 Plot a graph of time squared (t^2) on the horizontal axis vs height (s) on the vertical axis. This should give you a linearised graph.

6 Determine an equation for the linear trend line, and calculate the R^2 value. The gradient of the graph will be $\frac{s}{t^2}$.

7 Determine the uncertainty of the gradient using minimum and maximum lines of best fit. Note that horizontal error bars will need to be used as it is the time squared that has significant uncertainty, not the displacement.

8 Deduce the meaning of the uncertainty in the intercepts on the vertical axis (c).

9 Calculate the acceleration due to gravity, g, and state the absolute uncertainty and the range of values. Note that the gradient is equal to $\frac{s}{t^2}$ which equals $\frac{g}{2}$, hence $g = 2 \times$ gradient.

10 Compare the experimental value for the acceleration due to gravity with the accepted value by calculating the absolute and percentage errors in 'g'. You will need to look up the accepted value for your latitude and height above sea level.

Discussion

1 Evaluate whether the aim was achieved. You should discuss the reliability and validity of the experimental process with reference to the uncertainty and limitations of the data, such as measurement uncertainty and percentage error.

2 Identify justifiable sources of imprecision and inaccuracy and categorise them as random or systematic error.

3 Suggest improvements or extensions to the experiment using the uncertainty and limitations identified. These should be directed at allowing you to modify (i.e. refine, extend or redirect) the design or method for use in a future Student Experiment in order to address your own related hypothesis or question. Some possibilities include:
- Will video analysis provide more accurate data?
- Does the cross-sectional area of a falling object affect its rate of descent?
- Can 'g' be better estimated with a ball rolling down an incline?

10.2 MANDATORY PRACTICAL

Constructing and interpreting displacement–time and velocity–time graphs

Unit 2, Topic 1: Conduct an experiment that requires students to construct and interpret displacement–time and velocity–time graphs with resulting data. Where appropriate, students should use vertical error bars when plotting data. This ensures that they can determine the uncertainty of the gradient and intercepts using minimum and maximum lines of best fit.

Source: *Physics 2019 v1.2 General Senior Syllabus Queensland Curriculum & Assessment Authority*

Context

In this experiment you will examine the link between two common forms of graphs for motion of an object undergoing uniform acceleration. By using an inclined plane, as Galileo did almost 400 years ago, the motion of a rolling ball can be examined more effectively as it is moving so much slower. It is still the intention of this practical to measure the time using a stopwatch.

This will provide you with an opportunity to refine the design later for a Student Experiment, for example, using video analysis.

Aim

To construct and interpret displacement–time and velocity–time graphs for a ball rolling down an incline.

Materials

- Ball, smooth, perfectly round (ball bearing, billiard ball)
- Inclined plane (for example, aluminium channel, or a surface as smooth as possible)
- Blocks to raise one end (or retort stand and boss head)
- Stopwatch
- Metre ruler

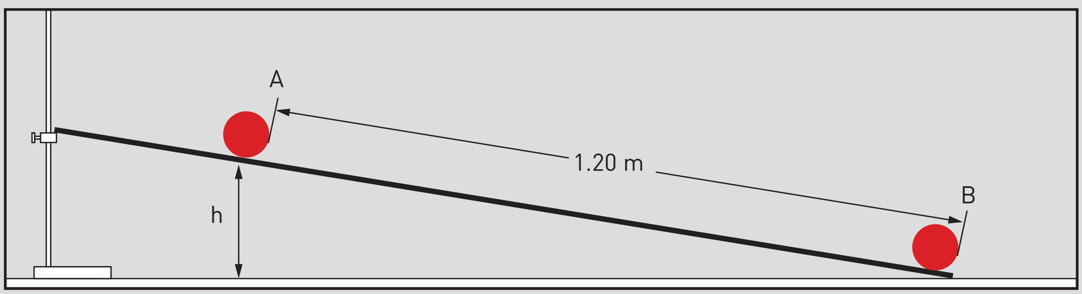


FIGURE 1 Experiment set-up

Method

1 Set up an inclined plane with a height that ensures a ball takes several seconds to roll its length. This will probably be just a few centimetres. Check the ramp being used doesn't have a sag in the middle from its own weight. Support it or use a stiffer material such as aluminium channel.

2 Decide on seven lengths (displacements) of the inclined plane from which to release the ball. The smallest should be no less than 20 cm from the lower edge, and the largest should be at least 5 times this. A convenient arrangement in a laboratory is a length of 1.2 m in increments of 20 cm. Mark these points on the ramp with a pen or tape as instructed.

3 Place a ball with its forward surface at the 20 cm mark (see diagram) and release it. Simultaneously start a timer, and stop the timer when the ball reaches the zero mark. Practise this a few times before recording your first data. You should decide on a method for starting and stopping the time to minimise error from reaction time. If you use your finger to hold the ball in place watch that you don't flick it backwards or forwards when you release it. Most students tend to do this without realising.

4 Do three replicate tests at this distance and record the data. Repeat this for the next trial length and so on until at least five distances are tested.

5 The scale reading uncertainty for a stopwatch is ± the least significant decimal place (probably ± 0.01 s) but this is overshadowed by the much larger uncertainty due to human reaction time (± 0.1 to 0.2 s). Your recorded times could show this scale reading uncertainty but as you are doing replicates the formula for uncertainty from repeated measures will be used: $\delta = \pm\frac{(x_{max} - x_{min})}{2}$. Calculate the absolute uncertainty using this formula and enter it in the final column. As well, calculate the percentage uncertainty. This is a useful measure of the reliability of your experiment.

Results

TABLE 1 Results table

Displacement s, (m) ± 0.005 m	Time, t (s) ± 0.2 s				Uncertainty	
	Test 1	Test 2	Test 3	Average	Absolute ± δ (m)	Percentage ± δ%
0.20						
0.40						
0.60						

1 It is usual to plot the independent variable on the horizontal axis, but in this case, graphical analysis is simplified by plotting it on the vertical axis. Hence, plot a graph of the independent variable **displacement**, s (vertical axis) vs the dependent variable **time**, t (horizontal axis). It should appear to show the relationship: $y \propto x^2$.

2 The equation $v = u + at$ shows that relationship between v and t is expected to be $y \propto x$ when the acceleration a (or g) due to gravity is constant and

the starting speed u is zero. To confirm this you will need to calculate the final velocity v for each trial. Because the motion is considered to be uniformly accelerated motion we can also assume that the final velocity is twice the average velocity ($v_f = 2 \times v_{av}$). Firstly, calculate the average velocity using $v_{av} = \frac{s}{t}$ then doubling each value to give the final velocity v_f(or just v). Record this in the table below. If you are computing this in a spreadsheet, extend your original data table.

TABLE 2 Results table

Displacement s, (m) ± 0.005 m	Time, t (s) ± 0.2 s	Uncertainty		Velocity, v (m s^{-1})		
		Absolute ± δ (m)	Percentage ± δ%	v_{av}	v_f	$\delta(v_f)$
0.20						
0.40						
0.60						
1.60						
2.00						

3 Calculate the absolute uncertainty (δ) in the value for velocity. As velocity is just displacement divided by the time, and we are assuming there is insignificant uncertainty in the displacement, we can say that the percentage uncertainty in the velocity is the same as the percentage uncertainty in the time. Use this percentage to calculate the absolute uncertainty $\delta(v_f)$ in the velocity. Add it to the table.

4 Plot a graph of time on the horizontal axis vs final velocity (v) on the vertical axis. This should give you a linear graph if acceleration is uniform. Determine the linear trend line and the equation for the graph. Note that the gradient $m = \frac{\Delta v}{\Delta t} = a$.

5 Add vertical custom error bars to your velocity data. You could also add horizontal error bars to your time data but the uncertainty in the gradients will be shown by the vertical error bars so you can leave the horizontal error bars out if you like.

6 Determine maximum and minimum lines of best fit and hence state the uncertainty in the gradients (acceleration).

7 Deduce the meaning of the uncertainty in the intercepts on the vertical axis (c).

Discussion

1 Evaluate whether the aim was achieved. You should discuss the reliability and validity of the experimental process with reference to the uncertainty and limitations of the data, such as measurement uncertainty and percentage error.

2 Identify justifiable sources of imprecision and inaccuracy and categorise them as random or systematic error.

3 Suggest improvements or extensions to the experiment using the uncertainty and limitations identified. These should be directed at allowing you to modify (i.e. refine, extend or redirect) the design or method for use in a future Student Experiment in order to address your own related hypothesis or question. Some possibilities include:

- Will video analysis provide more accurate data?
- Would a longer incline give more consistent results?

16.1 MANDATORY PRACTICAL

Refractive index of a transparent substance

CAUTION: ELECTRICAL EQUIPMENT CAN CAUSE ELECTRIC SHOCKS.
LIGHT BOXES CAN CAUSE BURNS.

Unit 2, Topic 2: Conduct an experiment to determine the refractive index of a transparent substance.

Source: *Physics 2019 v1.2 General Senior Syllabus Queensland Curriculum & Assessment Authority*

Context

The refractive index of a substance is defined by Snell's law, but to be certain of the value it is best to determine it using several measurements of the incident angle to ensure random errors are minimised.

Aim

To measure the refractive index of a transparent substance.

Materials

- Semicircular transparent perspex/plastic block
- Ray box kit (including light source and single-slit plate)

Method

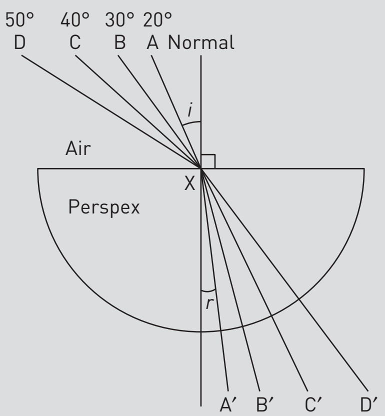


FIGURE 1 Set-up for the semicircular block

1. Place the semicircular block on graph paper and trace a line around it.
2. Draw as shown (Figure 1) and replace the semicircular block
3. Draw lines A, B, C, D (20°, 30°, 40°, 50°) as shown, using a protractor. Further angles can be added.
4. Set the ray box to give a single beam of light and place it so the ray is along line AX.
5. Mark the position of the ray XA′ as it exits the block, and mark any reflection using A′.
6. Repeat for lines B, C and D.
7. Remove the block and join the lines from A′, B′, C′, D′ to the point X.
8. Measure the angles of refraction using a protractor and enter in the table as r_1.
9. Draw a fresh diagram and repeat. Do not use the same diagram as your duplicates will suffer 'confirmation bias' as you will tend to draw over the same line again.
10. Add the new results to the table as r_2.

Results

TABLE 1 Results table

angle i	angle r_1	angle r_2	angle r_{av}	δ (r)	sin i	sin r_{av}	sin r_1	sin r_2	δ (sin r)
10.0									
20.0									
30.0									
40.0									
50.0									
60.0									
70.0									
80.0									

1 Calculate the average angle of refraction, r_{av}, and its uncertainty $\boldsymbol{r}_{av}$ (r).

2 The relationship between the angle of incidence and angle of refraction is not simple. They are related by the sine of the angles such that $\frac{\sin i}{\sin r}$ = a constant, n (*refractive index*). Calculate the sin of the angle of incidence (sin i), and the sin of the average angle of refraction (sin r_{av}), and the sin of each angle of refraction (sin r_1 and sin r_2 separately). Add these data the table.

3 Calculate the uncertainty, δ, in the sin of the angles of refraction using: $\delta = \pm\frac{(x_{max} - x_{min})}{2}$

4 Plot a graph of sin r (vertical axis) vs sin i (horizontal axis) and determine the equation for the line.

5 Add custom error bars using the uncertainty calculated in Step 3.

6 Draw maximum and minimum lines of best fit and determine the gradient of each.

7 The gradient is $\frac{\sin r}{\sin r}$ which is the reciprocal of refractive index. Calculate the reciprocal of the gradient for the linear line of best fit, and the reciprocal of the gradients of the maximum and minimum lines of best fit, and hence their refractive index values.

8 Calculate the uncertainty in the refractive index by using the maximum and minimum refractive indices: $\delta = \pm\frac{(x_{max} - x_{min})}{2}$.

9 The accepted value for acrylic plastic as used in these plastic blocks is 1.4900 (actually this is for light of a middle wavelength of 600 nm and does range from 1.485 to 1.502 for the visible region). Calculate the absolute error, Ea, and the percentage error, E%, in the experimental value.

Discussion

1 The uncertainty in the sin value of an angle can also be calculated by use of the formula: $\delta(\sin r) = \cos r \times \delta(r)$ with the uncertainty in radians. For example, if uncertainty in the angle of refraction of 30° was ± 1.5° (or 3/57.1 rad), then the uncertainty in sin 30° would be: cos 30° × 1.5/57.1 = 0.865 × 0.026 = ± 0.023. Determine whether this calculation produces similar uncertainties in sin r as your earlier method.

2 Evaluate whether the aim was achieved. You should discuss the reliability and validity of the experimental process with reference to the uncertainty and limitations of the data such as measurement uncertainty and percentage error.

3 Identify justifiable sources of imprecision and inaccuracy, and categorise them as random or systematic error.

4 Suggest improvements or extensions to the experiment using the uncertainty and limitations identified. These should be directed at allowing you to modify (i.e. refine, extend or redirect) the design or method for use in a future Student Experiment in order to address your own related hypothesis or question.

APPENDICES

Appendix 1 Properties of the nuclides

Z = atomic number = number of protons

A = atomic mass = number of protons plus neutrons

M = exact mass of the nuclide including electrons (in u)

Z		A	M	Z		A	M
–1	e	0	0.000549	37	Rb	90	89.914798
						93	92.922039
0	n	1	1.008665			96	95.934133
1	p	1	1.007276	38	Sr	88	87.905613
						90	89.907730
1	H	1	1.007825			93	92.914024
		2	2.014102			94	93.915356
		3	3.016050			96	95.921707
2	He	3	3.016029	39	Y	90	89.907144
		4	4.002603	40	Zr	94	93.906311
		6	6.018886	42	Mo	100	99.907472
		8	8.033934	47	Ag	107	106.905092
3	Li	6	6.015123			108	107.905950
		7	7.016003	48	Cd	113	112.904408
		8	8.022486	49	In	115	114.903879
		9	9.026790			116	115.905260
4	Be	6	6.019726	50	Sn	116	115.901743
		7	7.016929	52	Te	137	136.925599
		9	9.012183	54	Xe	135	134.907228
5	B	8	8.024607			139	138.918792
		10	10.012937			140	139.921646
		11	11.009305	55	Cs	130	129.906709
6	C	9	9.031037			135	134.905977
		10	10.016853			138	137.911017
		11	11.011434			141	140.920045
		12	12.000000	56	Ba	136	135.904576
		13	13.003355			141	140.914403
		14	14.003242			142	141.916432
7	N	12	12.018613			143	142.920625
		13	13.005738			144	143.922955
		14	14.003074	81	Tl	208	207.982019

Z		A	M	Z		A	M
8O		13	13.024815	82	Pb	206	205.974466
		16	15.994915			208	207.976652
		17	16.999132	83	Bi	212	211.991286
		18	17.999160	84	Po	212	211.988868
11	Na	22	21.994437			216	216.001915
		23	22.989769	86	Rn	220	220.011394
		24	23.990963			222	222.017578
12	Mg	23	22.994124	88	Ra	224	224.020212
13	Al	27	26.981539			226	226.025410
15	P	30	29.978314			228	228.031071
		31	30.973762	89	Ac	228	228.031022
		32	31.973908	90	Th	234	234.043601
16	S	32	31.972071	91	Pa	234	234.043307
		35	34.969032	92	U	233	233.039636
17	Cl	36	35.968307			234	234.040952
19	K	40	39.963998			235	235.043930
26	Fe	56	55.934936			236	236.045568
27	Co	60	59.933816			238	238.050788
28	Ni	60	59.930786			239	239.054293
		61	60.931056	93	Np	239	239.052939
		64	63.927967	94	Pu	239	239.052164
29	Cu	64	63.929764			240	240.053814
30	Zn	64	63.929142			241	241.056852
		65	64.929241	95	Am	239	239.053025
36	Kr	84	83.911498			241	241.056829
		90	89.919528				
		91	90.923806				
		92	91.926173				

Source: International Atomic Energy Agency. Extract from *Senior Physics* 3rd Edition 2018 Walding

Appendix 2 Periodic table

6	Atomic number
C	Chemical symbol
12.01	Atomic mass
Carbon	Name of element

Period	1 Group	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H 1.01 Hydrogen																	2 He 4.00 Helium
2	3 Li 6.94 Lithium	4 Be 9.01 Beryllium											5 B 10.81 Boron	6 C 12.01 Carbon	7 N 14.01 Nitrogen	8 O 16.00 Oxygen	9 F 19.00 Fluorine	10 Ne 20.18 Neon
3	11 Na 22.99 Sodium	12 Mg 24.31 Magnesium											13 Al 26.98 Aluminium	14 Si 28.09 Silicon	15 P 30.97 Phosphorus	16 S 32.07 Sulfur	17 Cl 35.45 Chlorine	18 Ar 39.95 Argon
4	19 K 39.10 Potassium	20 Ca 40.08 Calcium	21 Sc 44.95 Scandium	22 Ti 47.88 Titanium	23 V 50.94 Vanadium	24 Cr 52.00 Chromium	25 Mn 54.95 Manganese	26 Fe 55.85 Iron	27 Co 58.93 Cobalt	28 Ni 58.70 Nickel	29 Cu 63.55 Copper	30 Zn 65.39 Zinc	31 Ga 69.72 Gallium	32 Ge 72.61 Germanium	33 As 74.92 Arsenic	34 Se 78.96 Selenium	35 Br 79.90 Bromine	36 Kr 83.80 Krypton
5	37 Rb 85.47 Rubidium	38 Sr 87.62 Strontium	39 Y 88.91 Yttrium	40 Zr 91.22 Zirconium	41 Nb 92.91 Niobium	42 Mo 95.94 Molybdenum	43 Tc 97.00 Technetium	44 Ru 101.07 Ruthenium	45 Rh 102.91 Rhodium	46 Pd 106.40 Palladium	47 Ag 107.87 Silver	48 Cd 112.41 Cadmium	49 In 114.82 Indium	50 Sn 118.71 Tin	51 Sb 121.76 Antimony	52 Te 127.60 Tellurium	53 I 126.90 Iodine	54 Xe 131.29 Xenon
6	55 Cs 132.91 Caesium	56 Ba 137.33 Barium	57 to 71	72 Hf 178.49 Hafnium	73 Ta 180.95 Tantalum	74 W 183.85 Tungsten	75 Re 186.21 Rhenium	76 Os 190.23 Osmium	77 Ir 192.22 Iridium	78 Pt 195.08 Platinum	79 Au 196.97 Gold	80 Hg 200.59 Mercury	81 Ti 204.38 Thallium	82 Pb 207.20 Lead	83 Bi 208.98 Bismuth	84 Po 209.00 Polonium	85 At 210.00 Astatine	86 Rn 222.00 Radon
7	87 Fr 223.00 Francium	88 Ra 226.03 Radium	89 to 103	104 Rf 267.00 Rutherfordium	105 Db 270.00 Dubnium	106 Sg 269.00 Seaborgium	107 Bh 270.00 Bohrium	108 Hs 270.00 Hassium	109 Mt 278.00 Meitnerium	110 Ds 281.00 Darmstadtium	111 Rg 281.00 Roentgenium	112 Cn 285.00 Copernicium	113 Nh 286.00 Nihonium	114 Fl 289.00 Flerovium	115 Mc 290.00 Moscovium	116 Lv 289.00 Livermorium	117 Ts 294.00 Tennessine	118 Og 294.00 Oganesson

Metals

Rare earth elements
Lanthanoid series

57 La 138.91 Lanthanum	58 Ce 140.12 Cerium	59 Pr 140.91 Praseodymium	60 Nd 144.24 Neodymium	61 Pm (145) Promethium	62 Sm 150.4 Samarium	63 Eu 151.97 Europium	64 Gd 157.25 Gadolinium	65 Tb 158.93 Terbium	66 Dy 162.50 Dysprosium	67 Ho 164.93 Holmium	68 Er 167.26 Erbium	69 Tm 168.93 Thulium	70 Yb 173.04 Ytterbium	71 Lu 174.97 Lutetium

Actinoid series

89 Ac 227.03 Actinium	90 Th 232.04 Thorium	91 Pa 231.04 Protactinium	92 U 238.03 Uranium	93 Np 237.05 Neptunium	94 Pu 244.00 Plutonium	95 Am 243.00 Americium	96 Cm 247.00 Curium	97 Bk 247.00 Berkelium	98 Cf 251.00 Californium	99 Es 252.00 Einsteinium	100 Fm 257.00 Fermium	101 Md 258.00 Mendelevium	102 No 259.00 Nobelium	103 Lr 260.00 Lawrencium

METALS
- alkali metal
- alkaline earth metal
- lanthanide
- actinide
- transition metals
- post-transition metals

NON-METALS
- diatomic non-metals
- polyatomic non-metals
- noble gases

OTHER
- metalloids
- unknown chemical properties

GLOSSARY

A

absolute refractive index
the ratio of the velocity of light in air to the velocity of light in a different medium

absolute zero
the lowest temperature that is theoretically possible, at which the motion of particles which constitutes heat would be minimal. It is zero on the Kelvin scale

acceleration
the rate of change of an object's velocity (symbol: a; SI unit symbol: $m\ s^{-2}$)

accuracy
the difference between the measured value and the true or accepted value of the observed quantity

activity
the average number of disintegrations of a radioactive nuclide per second (symbol, A; unit: becquerel; unit symbol: Bq)

adhesion
the tendency of dissimilar surfaces to cling to one another by electrostatic and other forces

agent
the body that produces the force

alpha decay
the emission of a ${}^{4}_{2}He$ nucleus (2 protons, 2 neutrons) from the parent nucleus

alpha radiation
stream of particles each consisting of two protons and two neutrons tightly bounded together, emitted from the nucleus of some radionuclides (symbol, α or ${}^{4}_{2}He$)

ammeter
a device for measuring the rate of flow of charge (current) in a circuit

amplitude
the distance of a point, in a wave, from the rest position (equilibrium position) to the crest position, which is half the vertical distance from a trough to a crest

angle of incidence
the angle between the normal and direction of propagation of an incident wave

angle of reflection
the angle between the normal and direction of propagation of a reflected wave

anomaly
a false data point, often as the result of a faulty observation of wrong equipment

antineutrino
an elementary subatomic particle without electrical charge and a very small mass

antinodes
result from the intersection of two crests or two troughs producing super crests and troughs

antiparticle
a particle with the same mass and opposite charge to a corresponding particle, for example positron and electron

applied force
a force applied to an object by a person or another object; can be a push or a pull

artificial transmutation
a nuclear reaction induced artificially by means of bombardment with some fundamental particles

atom
the smallest particle of a chemical element that can exist

atomic number
the number of protons in an element's nucleus, Z

atomic weight
an older alternative term for relative atomic mass

B

balanced forces
two forces acting in opposite directions on an object, and equal in size; they do not cause a change in the motion of an object

becquerel
the SI unit of radioactivity, corresponding to one disintegration per second

best estimate
a value closest to the true value, usually found by taking repeated measurements and averaging

beta negative decay
emission of beta negative particles (electrons) from the parent nucleus

beta negative emission
stream of particles emitted from the nucleus identical to an electron (symbol β^{-})

beta positive decay
emission of beta positive particles (positrons) from the parent nucleus

beta positive radiation
stream of energetic positrons (and associated neutrinos) emitted from an atomic nucleus during beta positive decay

binding energy
the energy needed to overcome the forces holding a nucleus together to disassemble it into component parts

boiling point
the temperature at which a liquid changes into a vapour when the pressure of the vaporising liquid equals the surrounding pressure

boundary
a change in the media such as between springs of different weights, or an interface between two different materials such as a spring and the floor

C

calorimetry
the science of measuring the amount of heat transferred between objects or in a chemical reaction

Celsius scale
a temperature scale that takes absolute zero as −273.15 °C and the triple point of water (where solid, liquid and gas exist together), as 0.01 °C

centre of curvature
the centre of the circle that produces the curved surface of a lens

chain reaction
a series of nuclear fissions, each initiated by a neutron produced in a preceding fission

change in momentum
the final momentum minus the initial momentum

charge
one of the basic properties of the elementary particles (electrons and protons) which can be positive or negative, and occurs in whole number (discrete) units

chemical energy
microscopic potential energy contained in the bonds within and between particles

collision
when two or more objects hit each other

compression
a region in a longitudinal wave where the particles are closest together

conduction
a process in which heat is directly transferred or transmitted through a substance due to a temperature difference between neighbouring regions, without movement of any matter

conductor
a substance that allows free movement of charge through it

conservation of energy
the total energy of an isolated system remains constant

constant velocity
motion where the magnitude of the speed and direction of the object is not changing; this includes an object at rest

constructive interference
the interference of two or more waves of the same frequency and in phase with each other, superposing to produce an observable pattern in intensity

contact force
a force where the object and the action producing the force touch each other

convection
a transfer of heat caused by the movement within a fluid of the hotter and less dense material rising and colder, denser material, which sinks, under the influence of gravity

conventional current
the motion of charge in the same direction as the positive charge flow; opposite to electron flow

converging
bending of light rays together

converging lens
a lens that converges light (convex lens)

cooling
the process of transferring thermal energy away from a object to a cooler one

coulomb
a measure of electric charge. One coulomb (C) is the charge on 6.25×10^{18} elementary charges

crest
the highest part or point of a wave, or the points of maximum positive displacement

critical angle
the angle of incidence (symbol θ_c) for light in a more optically dense medium for which the angle of refraction in the less optically dense medium is 90° and resulting in total internal reflection

D

decay constant
the fraction of the number of atoms that decay in 1 second

decay rate
the time rate of the disintegration of radioactive material generally accompanied by the emission of particles and/or gamma radiation. Also known as activity

decay series
a chain of radioactive decays that produces a sequence of nuclides until a stable decay product, the end product, is formed

dependent variable (DV)
the variable (often denoted by y) that responds to the independent variable. It 'depends' on the independent variable.

destructive interference
the interference of two or more waves of the same, or almost the same frequency and 180° out of phase with each other, superposing to produce a resultant wave with reduced amplitude

deuterons
the nuclei of deuterium atoms, each consisting of a proton and a neutron

diffraction
the process by which waves either bend behind a barrier or the wavefront is broken up into many small sources

directed line segment
an arrow representing a vector in which the arrowhead represents the direction of the vector, and the length represents the magnitude

direction of propagation
the direction of energy flow in a wave

dispersion
the phenomenon in which the velocity of a wave depends on its frequency and is observed as the splitting of white light into a rainbow; this is due to the dependence of the index of refraction on the wavelength of light

displacement (linear motion)
a vector quantity representing the location of the destination relative to the origin of motion only, irrespective of the path actually taken between the two points (symbol: s; SI unit: metre; unit symbol: m)

displacement (wave motion)
the distance between a particle's position and the equilibrium position

dissipate
to lose energy (and hence, for a wave, amplitude) over time

distance
the total length of the pathway taken between the origin and the destination point; symbol d

disturbance
a displacement from the equilibrium position of a vibrating system

diverges
bending of light rays away from each other

diverging lens
a lens that diverges light (concave lens)

drag force
a force acting to oppose the motion of any object moving with respect to a surrounding fluid

dynamic friction
friction between surfaces in motion relative to each other. Also known as sliding or kinetic friction

E

elastic collision
a collision in which kinetic energy is conserved

electric current
the rate of motion of electric charge carriers from one part of a conductor to another (symbol: I; SI unit: ampere; unit symbol: A)

electric potential
the amount of work needed to move a unit (1 C) of charge from one point to another, or the electric potential energy per unit of charge (symbol: V; SI unit: volt; unit symbol: V)

electric potential energy
the amount of energy stored in a charge; or the capacity of the charge carriers to do work due to their position in an electric circuit (symbol: U; SI unit: joule; unit symbol: J)

electrical resistance
opposition to the flow of electric current in a circuit measured as the ratio of the voltage applied to the electric current that flows through it

electromagnetic radiation
radiant energy consisting of electromagnetic waves, propagated at the speed of light in a vacuum

electromagnetic waves
waves that require no medium for transmission and travel at the speed of light in a vacuum; includes long wavelength radio waves through to short wavelength gamma rays (called the electromagnetic spectrum)

electromotive force (EMF)
a difference in electric potential that produces an electric current (symbol: EMF; SI unit: volt; unit symbol: V)

electron current
the motion of charge in the same direction as electron charge flow; opposite to conventional flow

electron volt (eV)
a unit of energy defined as the work done on an electron in moving it through an electric potential difference of 1 volt

electron
a subatomic particle of mass 1836 times lighter than a proton with a −1 elementary electric charge, present in all atoms

electrostatic repulsion
the phenomena of two like charged particles repelling each other

elementary charge
the magnitude of the electric charge carried by a single electron or single proton

elementary particle
a particle whose substructure is unknown; for example, an electron or quark

energy
the capacity to do mechanical work (symbol: W; SI unit: joule; unit symbol: J)

energy transfer diagram
diagram that summarises all the energy transfers taking place in a process. The thicker the line or arrow, the greater the amount of energy involved

equilibrium
the natural or resting position assumed by a medium if no disturbance was travelling through it

explosion
when a single object separates into two or more fragments

extrapolation
a method of constructing new data points beyond the range of a set of known data points with the assumption that existing trends will continue

F

Fahrenheit scale
a temperature scale that takes the temperature at which water freezes into ice as 32 °F, and the boiling point of water as 212 °F

first law of thermodynamics
during an interaction between a system and its surroundings, the amount of energy gained by the system must be exactly equal to the amount of energy lost by the surroundings

focal length
the distance between the centre of a lens and its principal focus

force
a push or pull between objects that may cause an object or both objects to change speed and/or the direction of their motion or change their shape (symbol: F; SI unit: newton; unit symbol: N)

forced convection
the movement caused within a fluid generated by an external source such as a pump, fan, or suction device

forced vibration
the tendency of one object to force another adjoining or interconnected object into vibrational motion

force–time graph
depicts the force acting on an object as a function of time, with the area underneath being equal to the impulse

free-body diagram
used to show the relative magnitude and direction of all forces acting upon an object in a given situation

free convection
the movement caused within a fluid by the tendency of hotter and therefore less dense material to rise, and colder, denser material to sink under the influence of gravity, which consequently results in transfer of heat

free-fall motion
any motion of a body where gravity is the only force acting upon it

frequency
the number of oscillations of a wave source per second; measured in hertz (Hz)

friction
the force that resists motion between two surfaces in contact

fundamental forces
four forces that are mediated by one or more particles. They are, in order from strongest to weakest: the strong nuclear, the electromagnetic, the weak nuclear and the gravitational force

fundamental frequency
the lowest natural frequency produced by an object or musical instrument

G

gamma decay
a form of radioactivity in which an unstable atomic nucleus dissipates energy by emitting gamma radiation

gamma radiation
extremely high-frequency electromagnetic radiation (high-frequency photons) emitted from the nucleus of some radionuclides (symbol, γ)

gradient
the slope of a graph

gravitational force
a force that acts through a gravitational field between objects with mass

gravitational potential energy
the energy stored in an object as a result of its position relative to another object to which it is attracted by the force of gravity (symbol: E_p; SI unit: joule; unit symbol: J)

gravity
the force of attraction between all masses in the universe

H

half-life
the time taken for half the radioactive atoms in a sample to decay

harmonic
an integer (whole number) multiple of the fundamental frequency

heat
the internal energy transferred throughout the heating process

heat engine
a device that receives heat from a high temperature source and converts part of this heat into work, and rejecting the remaining waste heat to a low temperature 'sink'

heating
the process of transferring thermal energy from a hot object to a cooler one

hydrogen bomb
a thermonuclear weapon that employs the fusion of isotopes of hydrogen

hypothesis
a considered opinion, theory or statement, based on research and evidence, about something that is yet to be tested

I

impulse
a vector quantity defined as the change in momentum of an object, which is the product of a force and the time interval over which the force acts

incident wave
an approaching wave

independent variable (IV)
a variable (often denoted by x) whose variation does not depend on that of another

inelastic collision
a collision in which total kinetic energy is not conserved

instantaneous speed
the speed as measured over a very small period (an instant) of time

instantaneous velocity
the rate of change of velocity over a short instant of time

insulator
a substance that does not allow free movement of charge through it

intensity
the average rate of flow of energy per unit area

interference
the combination of two or more waves to form a resultant wave

internal energy
the total (microscopic) potential energy and (microscopic) kinetic energy of the particles in a system

interpolation
a method of constructing new data points within the range of a set of known data points

ion
an atom that has lost or gained electrons

ionising radiation
radiation that can remove an electron from an atom and create a heavy positive ion and free electron

isotope
a form of an element with the same number of protons but a different number of neutrons

K

Kelvin scale
a temperature scale that takes absolute zero as 0 K and the triple point of water (where solid, liquid and gas exist together), as 273.15 K

kinetic energy
the energy due to the motion of an object, including the motion of particles in a substance (symbol: E_K; SI unit: joule; unit symbol: J)

Kirchhoff's current law (KCL)
at any node in an electrical circuit, electric charge is conserved such that the sum of the electric currents flowing into a node is equal to the sum of electric currents flowing out of that node

Kirchhoff's voltage law (KVL)
the energy inputs in a circuit equal the sum of energy output from loads in the circuit such that the directed sum of the electric potential differences around any closed network is zero

L

law of conservation of charge
the net amount of charge produced in any transfer process is zero

law of conservation of energy
the total energy of an isolated system remains

law of conservation of momentum
states that for two objects colliding in an isolated system, the total momentum before and after the collision is equal

linearising
a process of transforming non-linear data by applying a mathematical function to one of the variables so that the relationship between the variables becomes closer to a straight line

longitudinal waves
waves where the direction of oscillation of particles is parallel to the direction of energy transfer or wave movement

M

macroscopic energy
big or bulk forms of energy not at an atomic scale

mass defect
the difference between the mass of an intact nucleus and the sum of the component parts (Δm)

mass
a characteristic of a body's resistance to motion; also called inertia

maximum line of best fit
a line of best fit of maximum gradient within the bounds of the error bars

mechanical energy
the sum of potential energy and kinetic energy of an object; the energy associated with its motion and position

mechanical waves
waves that require an elastic medium for the transfer of energy

mechanical work
the capacity of a system with thermal energy

medium
an elastic substance such as air or water that allows for the transfer of energy in the form of a mechanical wave

melting
is a physical process where a solid undergoes a phase change to become a liquid

microscopic energy
energy of the particles that make up a substance including microscopic kinetic energy from the motion of particles and the microscopic potential energy of the chemical bonds and nucleus

minimum line of best fit
a line of best fit of minimum gradient within the bounds of the error bars

mode
different standing wave patterns formed in strings and air columns

momentum
a vector quantity, being the product of an object's mass and its velocity

N

natural frequency
the frequency at which an object will resonate when made to vibrate by an imposed frequency or force

neutrino
an elementary subatomic particle very similar to an electron, but without electrical charge and a very small mass

neutron
a subatomic particle of about the same mass as a proton but without an electric charge, present in all atomic nuclei except those of ordinary hydrogen

Newton's first law
an object maintains its state of rest or constant velocity motion unless it is acted on by an external unbalanced force

Newton's second law
the acceleration of an object is in the direction of the net external force acting on it and proportional to the size of the force and inversely proportional to the mass

Newton's third law
forces always occur in equal and opposite pairs

nodal point
a location along a standing wave where destructive interference occurs to produce a point of minimum amplitude

node
created by the interacting of a trough of one wave and a crest of another, producing a point of zero displacement

non-contact force
an action-at-a-distance force that acts on an object without coming physically in contact with

non-ohmic
one that doesn't follow Ohm's law

normal
a line perpendicular to a surface, barrier or boundary

nuclear energy
microscopic potential energy contained within the nucleus of an atom

nuclear fission
a nuclear reaction in which a large unstable nucleus splits, forming two (or more) smaller, more stable nuclei and releasing neutrons and energy

nuclear fusion
a nuclear reaction in which two or more light atomic nuclei react (fuse) to form one or more different, heavier atomic nuclei and subatomic particles

nuclear radiation
radiation in the form of elementary particles emitted by an atomic nucleus, as alpha, beta or gamma rays

nuclear reactions
a reaction, as in fission, fusion or radioactive decay, that alters the energy, composition, or structure of an atomic nucleus

nuclear stability
a measure of the stability of an isotope determined from the neutron/proton ratio and the total number of nucleons in the nucleus

nucleons
protons or neutrons found in the nucleus of an atom

nucleus
the positively charged central core of an atom, consisting of protons and neutrons and containing nearly all its mass

nuclides
a distinct kind of atom or nucleus characterised by a specific number of protons and neutrons

O

Ohm's law
electric current is proportional to voltage and inversely proportional to resistance

ohmic devices
those that follow Ohm's law

open circuit
an incomplete electrical circuit in which no charge flows

outlier
a value that is much smaller or larger than most of the other values in a set of data

P

parallel connection
one in which all the positive terminals of the cells are connected together, and all the negative terminals are connected together

particle
a minute portion of matter. When associated with the kinetic model they are mainly atoms and molecules

particle model of light
uses photons to describe the behaviour of light such as the photoelectrical effect and atomic spectra

percentage uncertainty
an indicator of uncertainty in which the range of values for a measurement result (the uncertainty) is expressed as a percentage of the average measurement or best estimate

period
the length of time taken for one wavelength to pass a given point (time for one oscillation)

phase
the position of a point in time on a waveform cycle; particles in phase have the same motion (velocity and amplitude) at a moment in time

polarisation (linear)
the process where light exists in the form of a plane wave in space (which is in contrast to unpolarised light that is composed of light waves that are vibrating in more than one plane)

polariser
a device that allows only one component of the electric field to pass

positron
a particle of matter with the same mass as an electron but an opposite charge

potential difference
the difference in electric potentials between two points in an electric field

potential energy
stored energy found in the chemical bonds and nucleus of a substance

power
the rate at which work is done or the rate at which energy is transferred or transformed

power dissipation
a measure of the rate at which energy is lost from an electrical system

precision
the uncertainty of the measurement

principal axis
the line joining the centre of curvature through the optical centre of the lens

principal focus
the point where incident rays of light parallel to the principal axis converge to a point on the other side of a converging lens, or where the rays appear to have diverged from for a diverging lens

proton
a subatomic particle of about the same mass as a neutron with a +1 elementary electric charge, present in all atomic nuclei

pulse
single disturbance produced in a medium by a source

Q

qualitative data
relating to the non-numerical characteristics of a substance or object

quantitative data
relating to numerical data about a substance, an object or a phenomenon

R

radiation
the transfer of energy in the form of electromagnetic waves or moving subatomic particles

radioactive
describes substances which have nuclei with an excess of energy and spontaneously emit radiation to reduce to excess energy

random errors
those due to the limitations (uncertainty) of the measurement equipment and the uncontrollable effects of a method and environment on a measurement result

rarefaction
a region in a longitudinal wave where the particles are furthest apart

real image
an image through which the rays of light from the object do actually pass

receiver
the body that responds to the force

reciprocal law
the refractive index for light passing from medium 1 to medium 2 is the reciprocal of the refractive index of light passing from medium 2 to medium 1

rectilinear propagation
the property of light that characterises it as travelling in a straight line in a uniform medium

reflected wave
the outgoing wave after reflection off a barrier

reflection
the process where incident waves at a boundary change direction returning into the same medium according to the law of reflection

refraction
the process when incident waves at a boundary change direction and speed when passing into another medium

relative atomic mass
the ratio of the average mass of atoms of an element (in a given sample) to one unified atomic mass unit

reliability
the ability to be trusted to be accurate or correct, or to provide a correct result

reliable
constant and dependable, or consistent and repeatable

resistivity
a fundamental property of matter that quantifies how strongly a given material opposes the flow of electric current

resistor
a device that reduces the flow of charge (current) in a circuit

resonance
when a vibrating object or external force causes another system to oscillate with greater energy at a particular frequency

resultant
the vector sum of two or more vectors

rolling friction
friction between two surfaces rolling over each other. It is the smallest of all three

S

scalar quantity
a quantity that has a magnitude but no direction

scale reading limitations
the inability of an instrument to resolve small measurement differences

scientific notation
a shorthand way of expressing very large or very small numbers in terms of a decimal number between 1 and 10 multiplied by a power of 10

series connection
one in which positive and negative electrodes of the cells are connected

series
describes an electrical circuit where components are connected along a single path, so the same current flows through all of the components

significant figures
the digits of a number that are used to express it to the required degree of accuracy (abbreviated: sf)

Snell's law
when light travels from one medium to another, the ratio of the sine of the angle of incidence to the sine of the angle of refraction is equal to the refractive index

specific heat capacity
the thermal energy required to raise the temperature of kg of a substance by 1°C

specific latent heat of fusion
the amount of energy required to change 1 kg of a substance from solid to liquid at its melting point (symbol: L_f; unit: J kg^{-1})

specific latent heat of vaporisation
the thermal energy required to change kg of a liquid at its boiling point into a vapour (symbol: L_v; unit: J kg^{-1})

spectrum
the range of frequencies of electromagnetic radiation and their respective wavelengths

speed
the rate at which distance is covered

stable
characteristic of nuclides that are not radioactive and so (unlike radionuclides) do not spontaneously undergo radioactive decay.

standard deviation
a measure of the amount of variation of a set of data values. A low standard deviation means the data points tend to be close to the mean of the set, while a high standard deviation indicates that the data points are spread out over a wider range of values

standing waves
those with stationery vibration patterns formed due to the superposition of waves with particular frequencies

static friction
friction between surfaces stationary relative to each other. It is generally higher than dynamic friction

strong nuclear force
force that acts over very small distances in the nucleus to hold the nucleons together against the repulsive electrostatic forces between the positively charged protons. It is one of the four fundamental forces

superposition
when two or more waves overlap in space, the resultant wave is the algebraic sum of the individual waves

systematic errors
those that cause readings to deviate from the accepted value by a consistent amount and in the same direction each time a measurement

is made. They are affected by the accuracy of a measurement process

T

temperature
a measurement of the warmth or coldness of an object or substance with reference to some standard value, e.g. the Celsius temperature scale

tension
the pulling force transmitted along a rope, string, cable or chain on an object

terminal velocity
velocity reached when the speed of an object falling through fluid becomes constant

thermal efficiency
the ratio of useful work out of a machine or in a process, total energy expended or heat taken in; often expressed as a percentage (symbol: η)

thermal energy transfer
the process of transferring thermal energy from one object to another, also known as heat

thermal energy
the internal energy present in a system due to its temperature. It does not include nuclear energy (symbol: U; unit: joule; unit symbol: J)

thermal equilibrium
the situation when there is no net exchange of thermal energy between any components of a system, i.e. the components have the same temperature and the average kinetic energy of the particles is equal

thermal expansion
the tendency of matter to change in shape, area, and volume in response to a change in temperature

total internal reflection
the phenomenon whereby all energy is reflected inside a medium due to the incident angle of the wave being greater than the critical angle

total momentum
the vector sum of individual momenta

transmission
the passage of a wave from one medium to another

transverse waves
waves where the direction of oscillation of particles is perpendicular to the direction of energy transfer

trough
the lowest part or point of a wave, or the points of maximum negative displacement

U

unbalanced forces
forces that cause a change in the motion of an object; also called non-balanced forces

uncontrolled fusion
a nuclear reaction in which the resulting energy is released in an uncontrolled manner, as it is in thermonuclear weapons (hydrogen bombs) and in most stars

uniform accelerated motion
motion where the velocity is not changing in magnitude or direction

V

vaporisation
a physical process where liquid undergoes a phase change to become a vapour (it can include evaporation or boiling)

vector addition
two or more vector quantities can be combined to produce a single resultant vector

vector quantity
a quantity that has both magnitude and direction

velocity
the rate of change of displacement of an object

virtual image
an image through which the rays of light from the object do not actually pass but only appear to pass

voltage
a measure of electric potential energy per unit charge, measured in joules per coulomb; often referred to as electric potential

voltmeter
an instrument used for measuring electric potential difference between two points in an electric circuit

volts
a unit of electric potential or voltage, equivalent to 1 joule per coulomb of charge

W

wave equation
given by the formula $v = f\lambda$ that relates the velocity of a wave propagating through a medium to the frequency and wavelength of the disturbance

wave model of light
uses the characteristics of waves such as wavelength, frequency and speed to describe the behaviour of light such as interference and refraction

wavelength
the minimum distance between two points on the wave in a phase

weight
a measure of the force of gravity acting on an object

work
the product of the force and the distance moved in the direction of an applied force

Z

zeroth law of thermal equilibrium
if two bodies are in thermal equilibrium with a third body, they are in thermal equilibrium with each other

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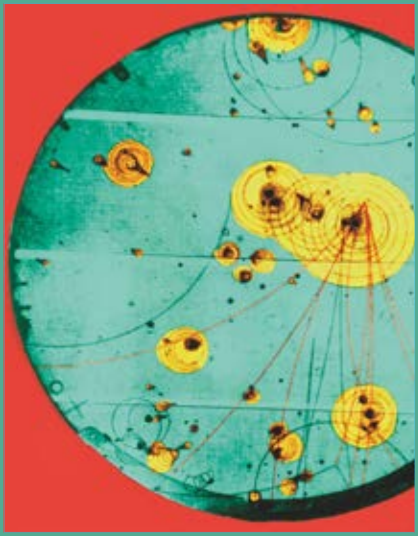

The front cover shows tracks produced in a bubble chamber after a collision between a hydrogen nucleus and a high-energy photon. A bubble chamber is an apparatus developed in 1952 to detect electrically charged particles. When ionising particles pass through the superheated liquid in a bubble chamber (usually hydrogen), they leave a trail of tiny bubbles.

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