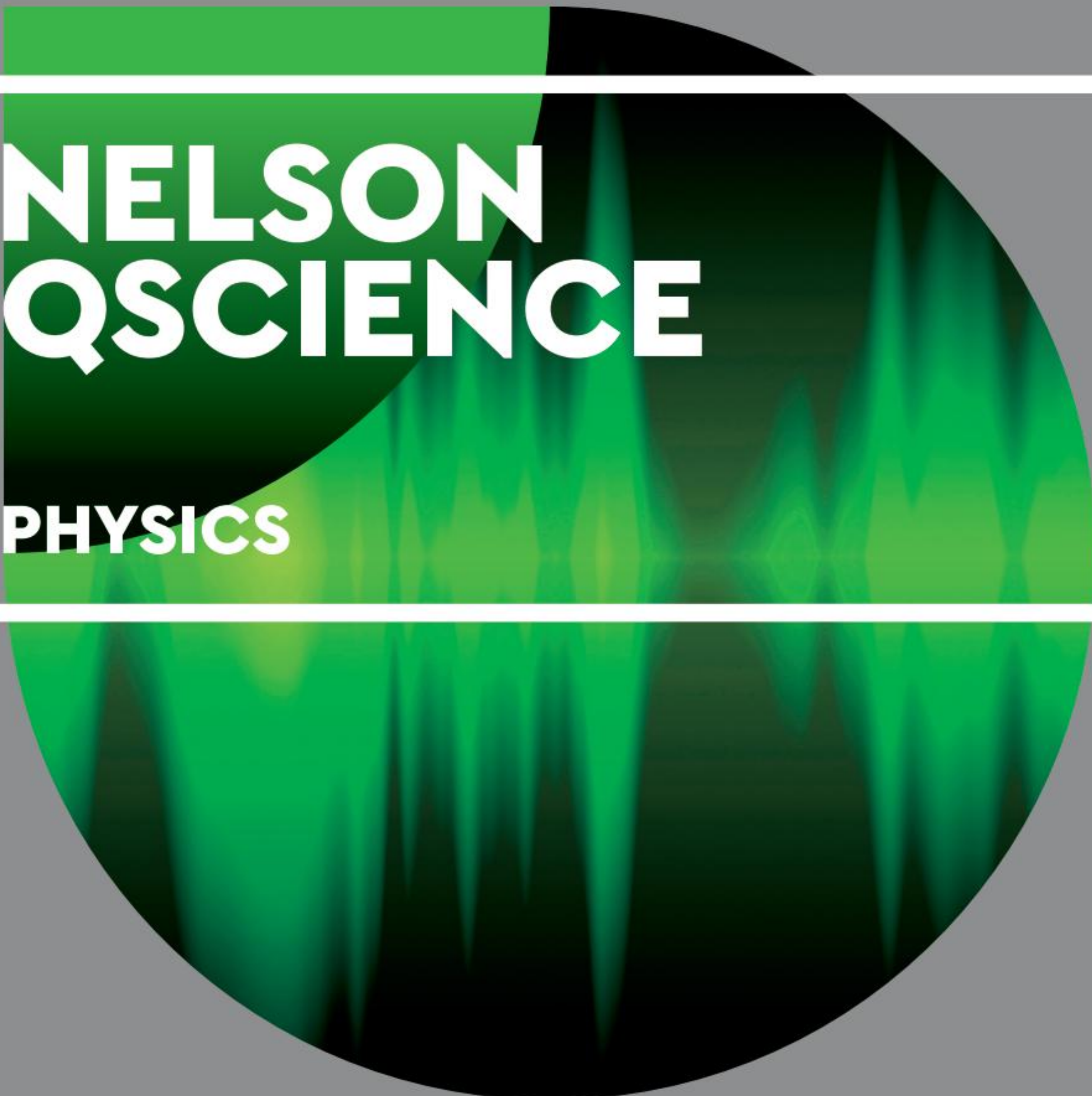

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PHYSICS

UNITS 1 2

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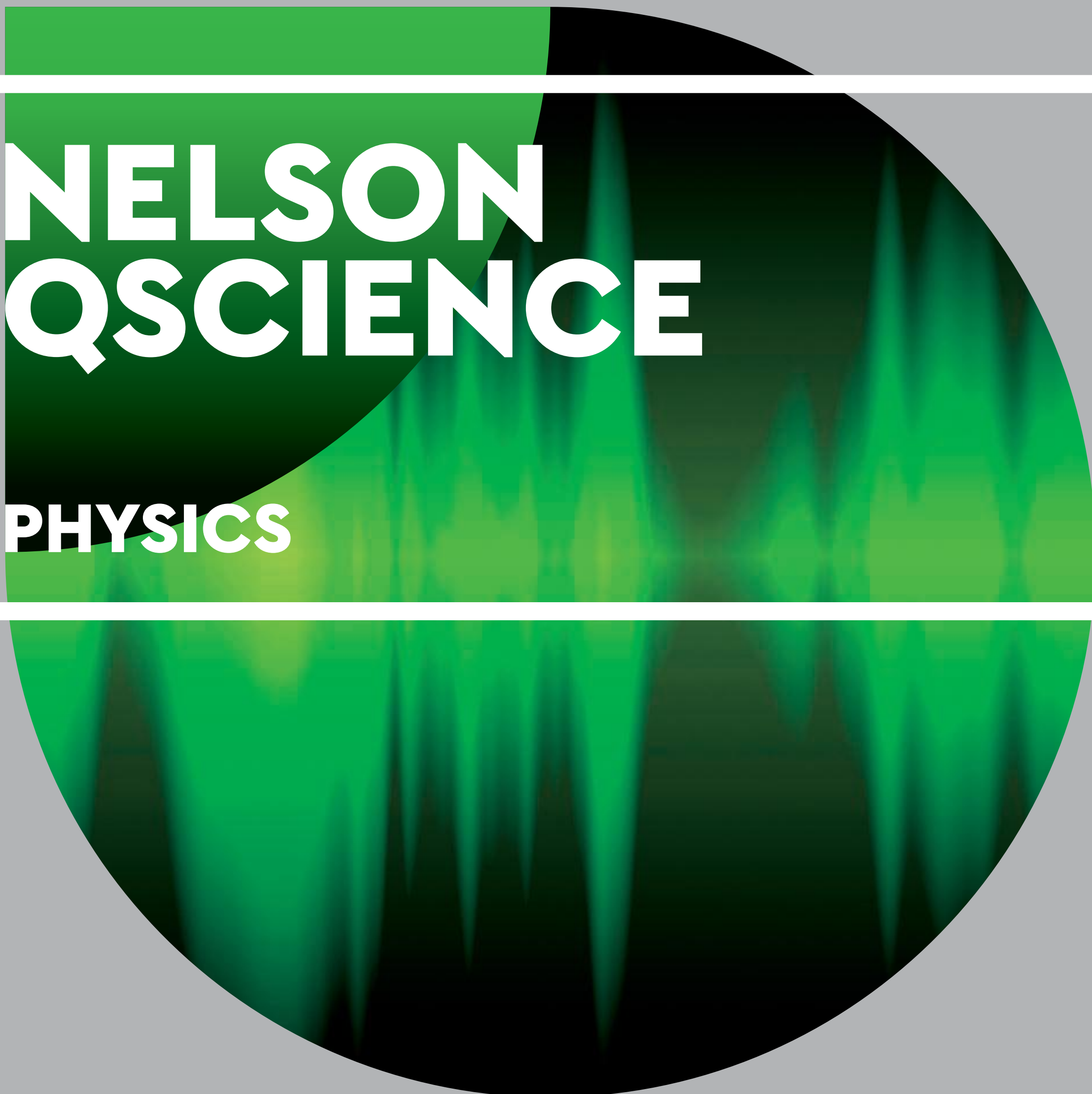

NELSON QSCIENCE

PHYSICS

UNITS 1 2

Scott Adamson
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Nelson QScience Physics Units 1 & 2
1st Edition
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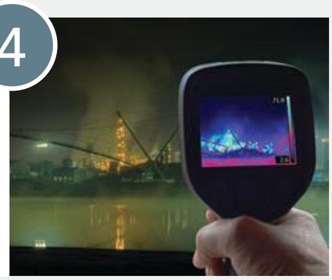

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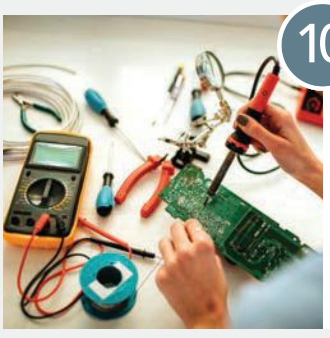

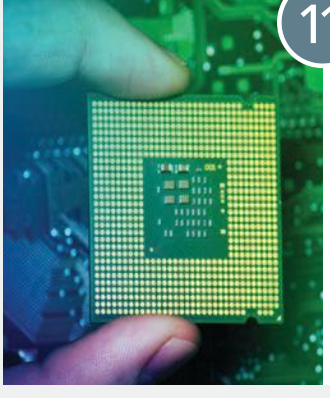

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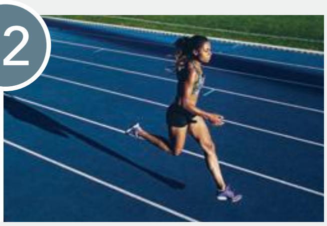

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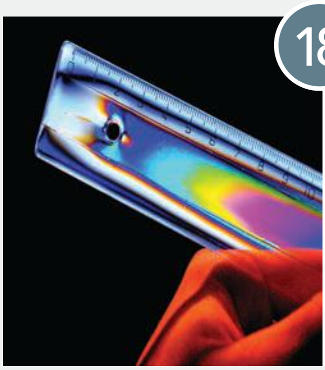

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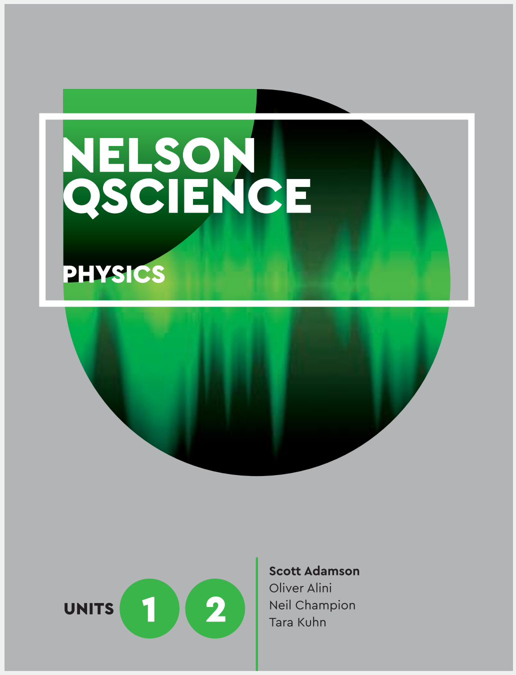
PREFACE

Nelson QScience Physics Units 1 & 2 has been written to meet the requirements of the QCAA Senior Secondary Science Syllabus – Physics. Each page has been carefully considered to provide students with all of the information they need to meet the content and skills requirements of the new syllabus.

With the introduction of the QCE external examination, *Nelson QScience Physics Units 1 & 2* includes features such as practice exams at the end of each chapter, a Units 1 & 2 practice exam, chapter quizzes (available on NelsonNet) and ExamView (available on NelsonNet).



AUTHORS AND REVIEWER TEAM

Nelson QScience Physics is adapted from *Nelson Physics for the Australian Curriculum Units 1 & 2* and *Nelson Physics for the Australian Curriculum Units 3 & 4* by Neil Champion, Robert Farr, Megan Mundy, Geoff Cody and Kate Wilson.

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An experienced science teacher, Tara brings her enthusiasm for physics and maths to the writing team.

NelsonNet

All NelsonNet material for QScience has been written by Stephen Bird and Louise Munro.

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The following people have contributed to the review of the *QScience* series: David Austin, Professor Alan E.W. Knight, Rebecca Delaney and Catherine Munro.

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SYLLABUS REFERENCE GRID

UNITS AND TOPICS	*NELSON QSCIENCE PHYSICS UNITS 1 & 2*
UNIT ONE » THERMAL, NUCLEAR AND ELECTRICAL PHYSICS	
TOPIC 1 HEATING PROCESSES	
Kinetic particle model and heatflow	Chapter 1
Temperature and specific heat capacity	Chapter 2
Phase changes and latent heat	Chapter 3
Energy conservation in calorimetry	Chapter 4
Energy in systems – mechanical work and efficiency	Chapter 5
TOPIC 2 IONISING RADIATION AND NUCLEAR REACTIONS	
Nuclear model and stability	Chapter 6
Spontaneous decay and half-life	Chapter 7
Nuclear energy and mass defect	Chapter 8
TOPIC 3 ELECTRICAL CIRCUITS	
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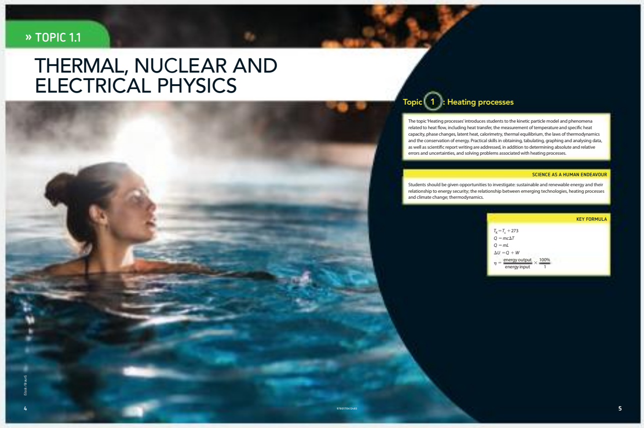
ABOUT THIS BOOK

At the beginning of each unit and topic

- Unit introductions are an overview of the key content in the unit.
- Topic introductions are an overview of the key content in the topic.



At the beginning of each chapter

- A short chapter summary introduces students to the key content and skills covered.
- Stimulus questions are relevant to the syllabus.

In each chapter

- **Worked examples** are explained clearly step-by-step.
- **Key formulas** are highlighted.
- **Key glossary terms** are highlighted in the margin.
- **Science as a Human Endeavour** provide opportunities for students to connect to the importance of SHE and develop scientific research skills.
- **Inquiring further** provides opportunities for students to further investigate scientific concepts and develop scientific research skills.
- **Section reviews** are written in the style of Bloom's revised taxonomy.
- **Practical experiments** contain guided instructions on the materials, procedure, collection and analysis of results and discussion.

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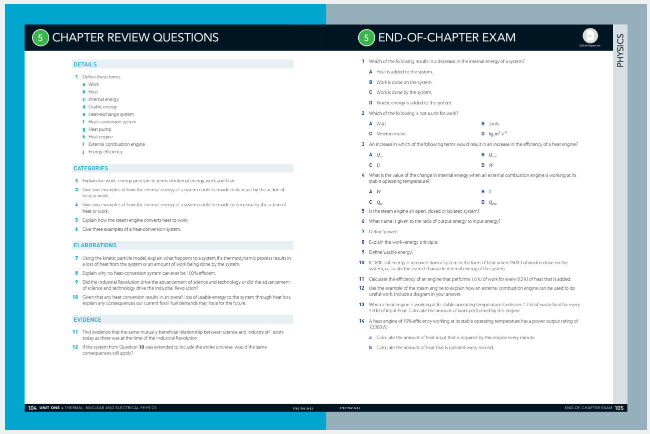
At the end of each chapter

- **Chapter review questions** are written in the style of Marzano and Simms (2014) questioning sequences.
- **End-of-chapter examinations** occur at the end of each chapter to help students develop skills in decoding and answering exam-style questions.



At the end of the book

- **Practice exam** questions provide an extended practice of the content and skills learnt across the text.
- **Glossary** provides explanation for all the new terms introduced in the text.
- **Answers** provide complete answers for student reference.

NelsonNet

NelsonNet is the protected portal to the premium digital resources for Nelson textbooks. Once registration is complete, exciting and stimulating digital is available for each of the chapters. The *Nelson QScience Physics Units 1 & 2* website is located at http://NQSP1-2QLD1e.nelsonnet.com.au.

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- End-of-chapter tests
- Weblinks

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» UNIT ONE

THERMAL, NUCLEAR AND ELECTRICAL PHYSICS

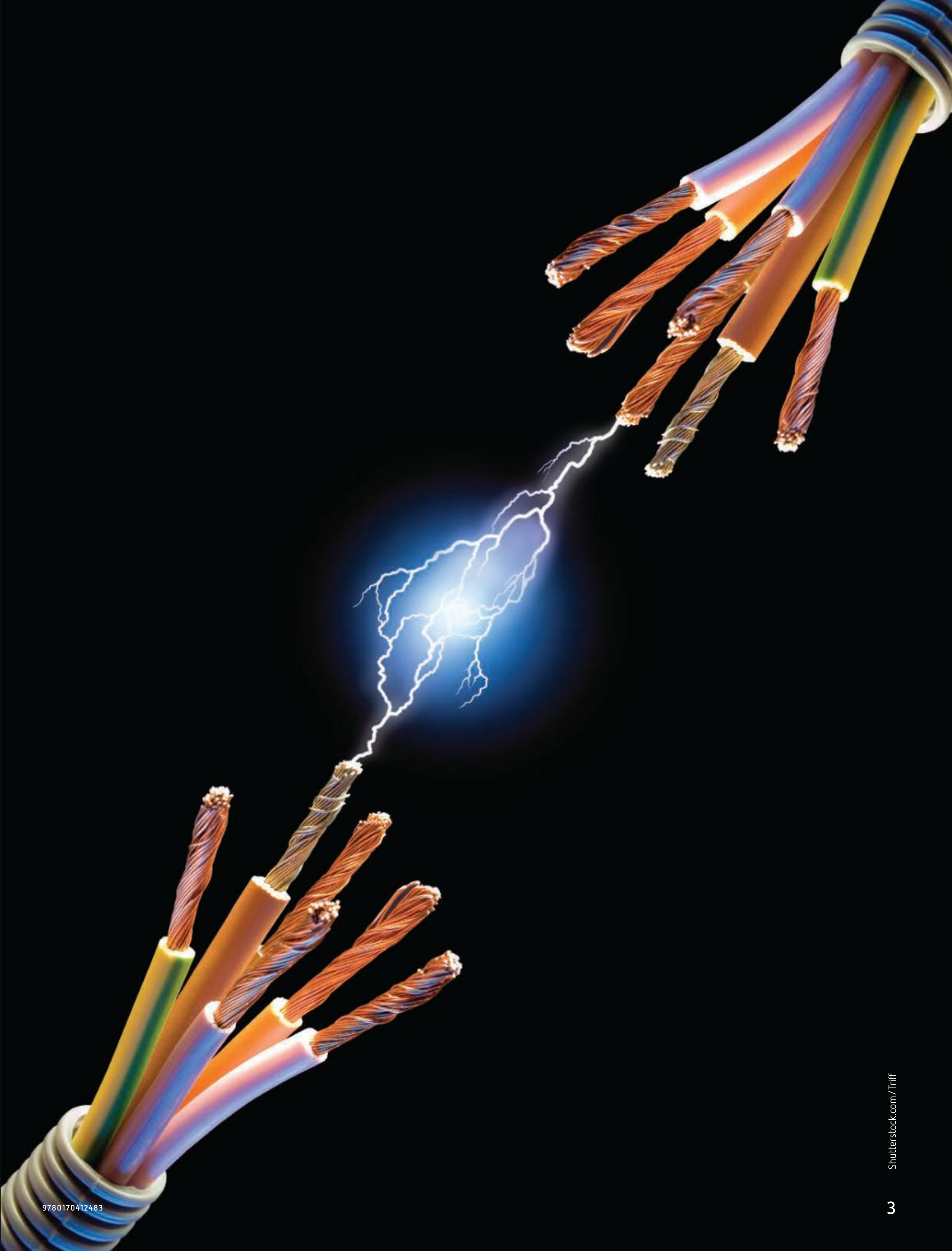
- Topic 1: Heating processes
- Topic 2: Ionising radiation and nuclear reactions
- Topic 3: Electrical circuits

Unit 1: Thermal, nuclear and electrical physics provides a basis for student exploration of how physics is used to describe, explain and predict energy transfers and transformations pivotal to modern society. Understanding heating processes, nuclear models, nuclear reactions and radioactivity, as well as electrical energy and circuit design, will allow the student to appreciate global energy needs and how they may be addressed in a socially, economically and ethically responsible way. Student inquiry and analytic skills are developed through experimentation, investigation, worked examples, questions and activities that offer opportunities for interpretation, construction of algebraic, graphical and symbolic representation and analysis of quantitative data and qualitative information.

UNIT OBJECTIVES

By the end of this unit, students should:

1. describe and explain heating processes, ionising radiation and nuclear reactions, and electrical circuits
2. apply understanding of heating processes, ionising radiation and nuclear reactions, and electrical circuits
3. analyse evidence about heating processes, ionising radiation and nuclear reactions, and electrical circuits
4. interpret evidence about heating processes, ionising radiation and nuclear reactions, and electrical circuits
5. investigate phenomena associated with heating processes, ionising radiation and nuclear reactions, and electrical circuits
6. evaluate processes, claims and conclusions about heating processes, ionising radiation and nuclear reactions, and electrical circuits
7. communicate understandings, findings, arguments and conclusions about heating processes, ionising radiation and nuclear reactions, and electrical circuits.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» TOPIC 1

THERMAL, NUCLEAR AND ELECTRICAL PHYSICS

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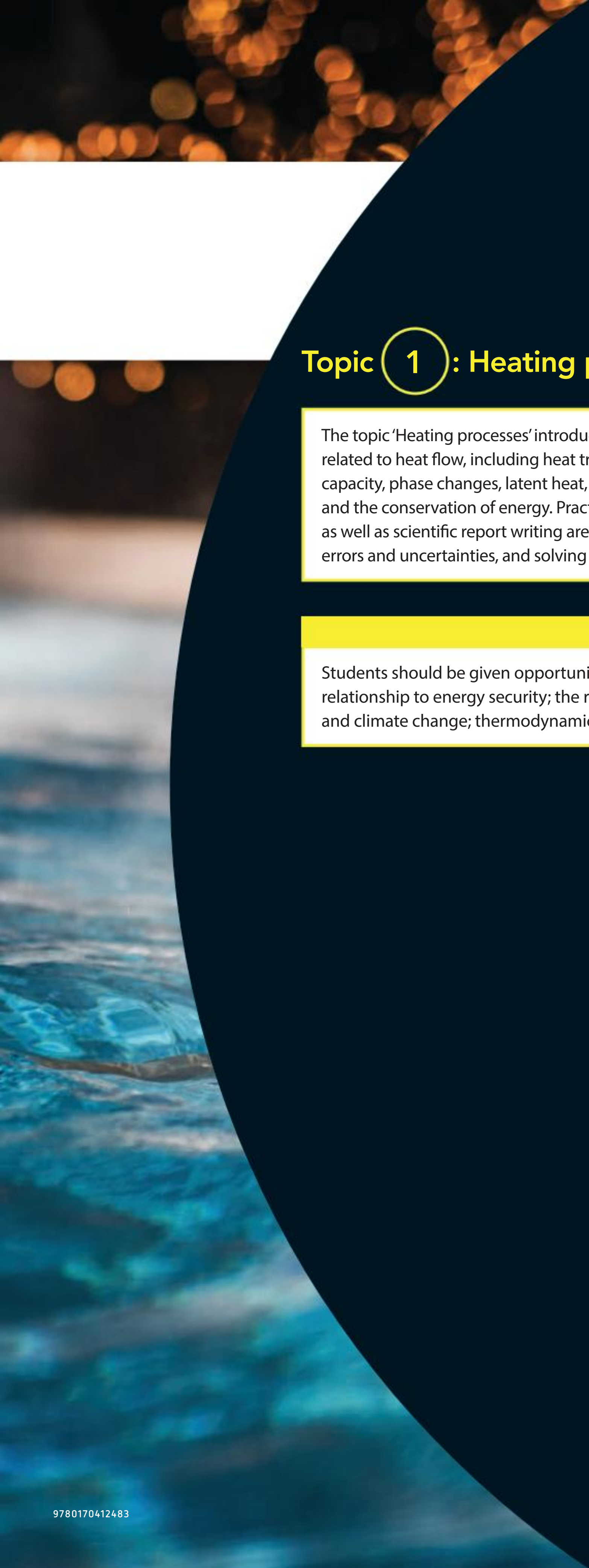

Topic 1: Heating processes

The topic 'Heating processes' introduces students to the kinetic particle model and phenomena related to heat flow, including heat transfer, the measurement of temperature and specific heat capacity, phase changes, latent heat, calorimetry, thermal equilibrium, the laws of thermodynamics and the conservation of energy. Practical skills in obtaining, tabulating, graphing and analysing data, as well as scientific report writing are addressed, in addition to determining absolute and relative errors and uncertainties, and solving problems associated with heating processes.

SCIENCE AS A HUMAN ENDEAVOUR

Students should be given opportunities to investigate: sustainable and renewable energy and their relationship to energy security; the relationship between emerging technologies, heating processes and climate change; thermodynamics.

KEY FORMULA

$T_K = T_c + 273$

$Q = mc\Delta T$

$Q = mL$

$\Delta U = Q + W$

$$\eta = \frac{\text{energy output}}{\text{energy input}} \times \frac{100\%}{1}$$

1 KINETIC PARTICLE MODEL AND HEAT FLOW

Introduction

Thermodynamics is a fundamental branch of physics that deals primarily with the study of energy, how it is transferred and how it affects matter. Even though it was first developed more than 200 years ago, it remains one of the most successful strands of physics. In particular, the study of thermal energy and how it is shared among particles is finely interwoven into many scientific disciplines, and has led to many significant scientific advancements and technological breakthroughs. Although its theoretical roots lie with the Ancient Greek idea of atoms, thermodynamics continues to drive much of today's cutting-edge research, including the origins of the universe, strange new states of matter and the direction of time.

In this chapter, the kinetic particle model will be explained in detail. It will be used to describe the concepts of heat, temperature, internal energy and how energy can be transferred between substances.

Stimulus questions

- What is heat?
- What is the difference between heat and temperature?
- What effect does an addition of heat or a change in temperature have on a substance?
- What happens to objects as their temperature approaches absolute zero?

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1.1 Kinetic particle model of matter

Matter can exist in four different states: solid, liquid, gas and plasma. Solids have fixed shapes, fixed volumes and are mostly incompressible. Liquids have fixed volumes, take on the shape of their container and are more or less incompressible. Gases have no fixed shape or volume and are compressible. Plasmas are similar to gases but are made up of charged particles.

The kinetic particle model of matter is used to explain a number of observations including the properties of the different states of matter, how the properties of matter change with the addition of thermal energy and how matter can change between states.

The kinetic particle model is centred on the Ancient Greek idea that if a small piece of matter were cut up into increasingly smaller pieces, there would come a point at which it could no longer be divided any further. This final piece was called an atom, which is Greek for 'indivisible'.

Even though today the atomic model is widely accepted, evidence to support it did not come until much later when, in the 18th and 19th centuries, the development of the microscope and the study of chemical interactions led to a deeper understanding of the movement of small particles.

One of the most significant discoveries that supported the atomic theory came in 1827 from the work of Robert Brown who, while observing the motion of tiny pollen grains suspended in water, noticed that even though the water was completely motionless, the grains still moved about in a completely random motion like that depicted in Figure 1.1.1. This observation is only reasonable if it is assumed that the particles of water are in continuous motion and constantly bump into each other. If this is accepted, then the movement of the pollen grains can be explained if their motion was continuously undergoing change under the influence of collisions with water particles.

The continuous motion of these particles, Brownian motion, forms the basis of the kinetic particle model. The model is successful in describing matter in the gaseous state. If the model is expanded to include two more assumptions (given on the next page), an important relationship between the average kinetic energy of the particles (atoms or molecules) and the overall temperature of the gas as a whole can be derived.

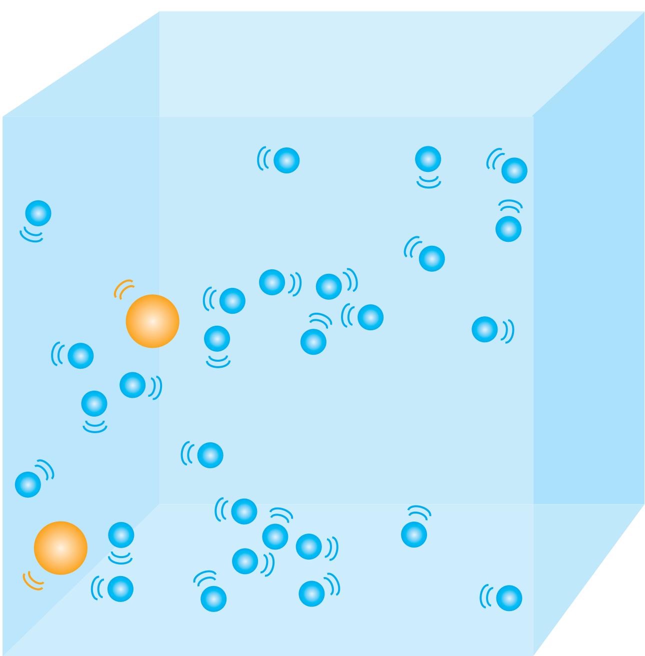

FIGURE 1.1.1 Robert Brown observed that tiny pollen grains suspended in water underwent continuous random motion despite the water being completely still. This is referred to as Brownian motion.

matter
a physical substance

plasma
a collection of free-moving electrons and ions that can be accelerated by magnetic and electric fields

kinetic particle model
the model that explains the properties of the different states of matter; the particles in solids, liquids and gasses have different amounts of energy, are arranged differently and move in different ways

atomic model
a series of descriptions relating to the fundamental structure of matter

Brownian motion
the random motion of small particles suspended in a fluid as a result of being bombarded by the particles of the fluid

molecule
a collection of atoms bound together by chemical bonds

derive
to obtain or create from base principles

SYLLABUS LINK

Chapter 6 of this book and Chapters 12 and 13 of *Nelson QScience Physics Units 3 & 4* discuss modern understandings of the atom.

1.1.1 Brownian motion

kinetic energy the energy of an object due to its motion

elastic collision a collision between two or more objects in which there is no loss of kinetic energy

potential energy energy that is stored in a system due to the configuration and interaction of the bodies within the system

The three assumptions of the kinetic particle model are as follows.

- All matter is made up of small particles in constant motion; they have **kinetic energy**.
- Collisions between particles are perfectly elastic; the total kinetic energy before and after the collision is the same.
- The particles obey classical mechanics and only interact with each other when they collide.

In an **elastic collision** kinetic energy is conserved. Kinetic energy is transferred from one particle to another, but not converted into **potential energy**. This model of a gas is the kinetic particle or **ideal gas** model. When these assumptions are made about a gas, we refer to the gas as an ideal gas. In this instance, it can be shown that the average kinetic energy of the particles in an ideal gas is directly proportional to the **temperature** of the gas.

KEY FORMULA

The average kinetic energy of an ideal gas is directly proportional to its temperature.

$E_{K\ average} \propto T$

Where:

$E_{K\ average}$ = average kinetic energy of the particles in a substance

T = temperature

The ideal gas equation states that the faster the particles of a gas are moving, the higher the temperature of the gas. This development of this relationship underpins our understanding of temperature.

Although this equation holds well for ideal gases, in reality, the last assumption of the kinetic model is not entirely correct in that the particles in substances interact even when they are not in the process of colliding. In all known substances, there is some degree of attraction between the particles within them.

The particles (atoms or molecules) are attracted to each other by **intermolecular forces** that bind them together and cause them to behave a bit like springs. There is an ideal length for any bond, but it is possible for the bond to be stretched and compressed. When this bond is stretched away from its ideal length by the movement of particles, the energy can be stored as **elastic potential energy**.

Ultimately, it is the balance achieved between the kinetic energy given to the particles because of the temperature of the substance and the strength of the intermolecular bonds that give rise to the particular state of matter that a substance is found in.

ideal gas a theoretical gas whose particles have no attraction to or repulsion from each other

temperature a measurement of the average kinetic energy of the particles in a substance

intermolecular forces electrostatic forces of attraction or repulsion between neighbouring particles of a substance

elastic potential energy energy that is stored by the deformation of an elastic object

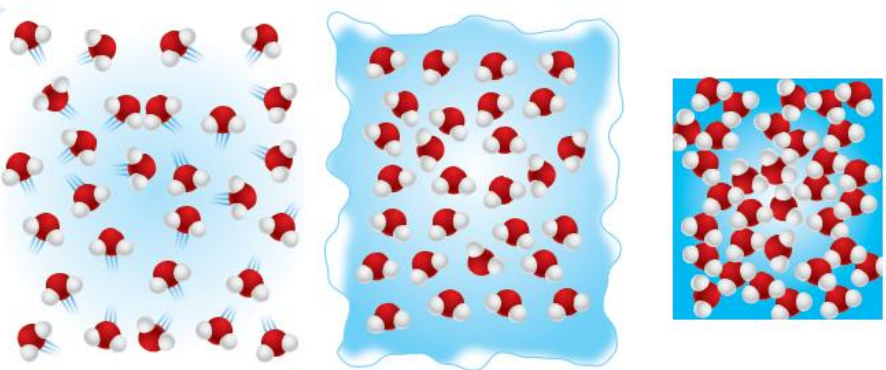

FIGURE 1.1.2 The states of matter showing approximate volume changes. (Note the change in scale: a mass of gas has a volume approximately 1600 times greater than the solid state.)

Gases

In a gas, which for a given substance occurs at higher temperatures than its liquid and solid state, the average kinetic energy of the molecules or atoms is large enough that they can break free from the bonds holding them together. The particles are free to move in any direction and only interact through elastic collisions. Generally, when they do collide, the force of attraction is too small to keep them close together.

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Liquids

In a liquid, the particles have less kinetic energy so that the bonds begin to have an effect, but they still only very loosely bind the particles together. There is potential energy associated with the interactions between the particles causing them to stay together, but they have enough kinetic energy so that they can slide over each other.

Solids

Finally, in a solid the kinetic energy of the particles is low enough that the intermolecular forces keep the particles bound together as a cohesive whole. Even though the material may not be going anywhere, every atom or molecule is still moving about constantly, vibrating or oscillating about its relatively fixed position. It is a bit like a large assembly of students all sitting in their own chairs, but each one fidgets and leans side to side to talk to their neighbours.

1.1.2 States of matter

SCIENCE AS A HUMAN ENDEAVOUR

SCIENCE AS A HUMAN ENDEAVOUR

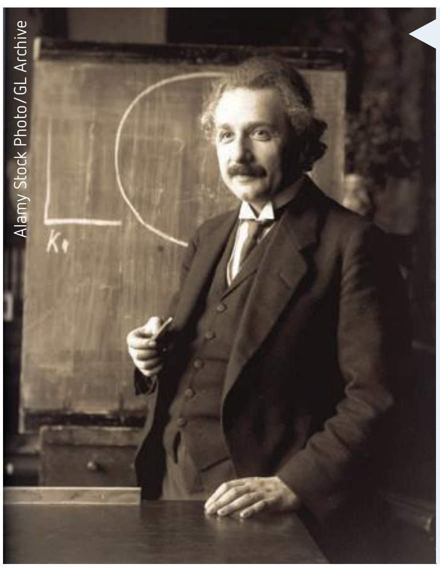
In 1924, an Indian physicist by the name of Satyendra Nath Bose sent a paper to Albert Einstein showing that simply by using probability and statistics, he could derive the **Planck radiation curve**. Einstein was so impressed by this work that he agreed to translate the paper into German and continued to work with Bose, extending his discovery.

In 1925, when extending the theory to a class of particles called **bosons**, Bose and Einstein realised that as these particles approached absolute zero, they would all 'condense' down into a form in which all atoms began occupying the same identical quantum state. They had effectively predicted a new physical state of matter. Unfortunately, they did not have the means to achieve very low temperatures at the time.

It was not until June 1995 that a group of physicists working at the University of Colorado were able to cool down a sample of rubidium gas to 0.000 000 170° above absolute zero and confirm the predictions of Einstein and Bose.

In honour of Satyendra Nath Bose and Albert Einstein, this new state of matter is now called a Bose–Einstein condensate. It exhibits many weird and wonderful properties, including the ability to slow light down to a fraction of its regular speed, the ability to act as one great big wave and the ability to climb up the walls of its containers. Physicists around the world are currently trying to find ways to utilise these properties.

Satyendra Nath Bose



Albert Einstein

FIGURE 1.1.3 The mathematical manipulations carried out by Satyendra Nath Bose and Albert Einstein predicted the existence of a new state of matter.

Planck radiation curve
a formula that describes the relationship between the electromagnetic radiation emitted by a substance and its temperature

boson
a particle with integer spin s = 0 or 1. These particles do not obey the exclusion principle

SECTION REVIEW

1.1

REMEMBERING

1. Identify the shape and volume traits of solids, liquids and gases.
2. Define 'Brownian motion'.
3. Identify the two types of energy that affect the motion of the particles in an object.
4. What causes the storage of energy in the form of elastic potential energy in the particles of an object?

UNDERSTANDING

5. If the temperature of an object increases, what must be happening to the average kinetic energy of its particles?
6. Explain the three states of matter in terms of their motion and intermolecular bonding.
7. Explain why the second law of thermodynamics suggests that absolute zero is unachievable.

1.2 The energy model

Energy exists in many forms, often named by their origin, including heat, light, mechanical, gravitational, electrical, magnetic, sound, chemical and mass. No matter the form, energy is still energy. All forms of energy can be *transformed* from one form to another and *transferred* from one place to another. For example, when you turn on an electrical bar heater, the electrical energy is transferred from the electrical wires to the heater, and in the process is transformed to radiant heat and light energy.

joule
SI unit of energy; $1\,J = 1\,kg\,m^2\,s^{-2}$

The SI unit of measurement of energy is the **joule** (J). It is approximately equivalent to the effort required to lift a 100 g apple from the ground to a height of 1 m.

The two major forms of energy are kinetic energy (energy associated with movement) and potential energy (energy ready to be used). All energy sources can ultimately be reduced to these two forms.

Kinetic energy

1.2.1 Kinetic energy

Kinetic energy is the energy a body possesses due to its motion. There are several forms of kinetic energy. Consider a moving train, for example (Figure 1.2.1). It has bulk translational kinetic energy due to the straight-line motion of the whole train. It has bulk rotational kinetic energy in the rotating wheels and engine parts. It has disorganised vibrational kinetic energy due to the vibrations of the atoms and molecules in the solid materials from which it is made.

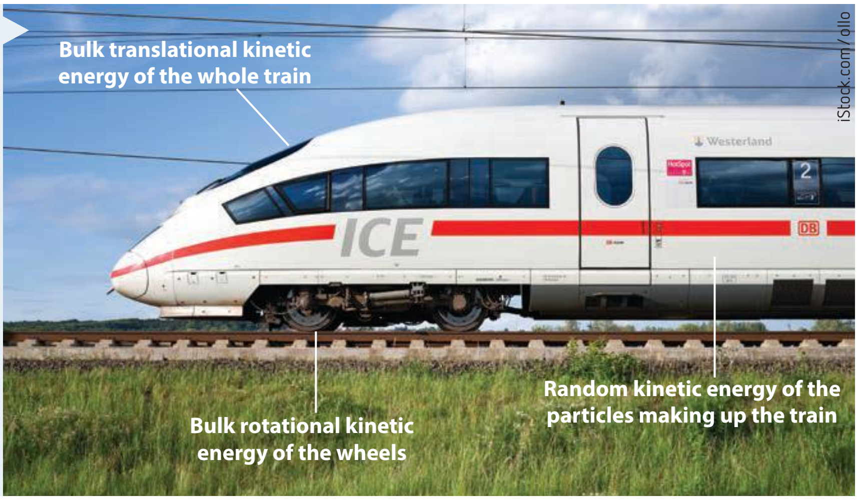


FIGURE 1.2.1 A moving train possesses different forms of kinetic energy.

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In the kinetic particle model, each atom or molecule in a substance has kinetic energy due to the random velocity that it has at any one time. It is important to remember that there is a range of kinetic energies that the particles may have, but that an average kinetic energy can be calculated.

When these particles collide elastically with each other, the total kinetic energy of the colliding particles before the collision is equal to the total kinetic energy of the particles after the collision. This can be written in the following two ways:

$$E_{K\ initial} = E_{K\ final} \qquad \Delta E_K = 0$$

KEY FORMULA

The conservation of kinetic energy in an elastic collision

$E_{K\ initial} = E_{K\ final} \qquad \Delta E_K = 0$

Where:

$E_{K\ initial}$ = initial kinetic energy of a particle

$E_{K\ final}$ = final kinetic energy of a particle

ΔE_K = change in kinetic energy of a particle

Potential energy

Stretching an elastic band does work to create stored energy, the potential to do work. When the elastic band is released, it transforms this stored energy to kinetic energy.

Potential energy is stored in the way the particles are connected to each other through the existence of intermolecular forces that form bonds between the particles. There is an ideal length for these bonds, but when the bonds are stretched or compressed by the kinetic energy of the particles, energy is stored as potential energy. This is like the energy that is stored in the bungee cord: when the cord is stretched, energy is stored as elastic potential energy; when the potential energy stored in the cord gets great enough, it can cause the jumper to spring back upwards against the force of gravity.

internal energy the sum of the kinetic energy of the particles in a system and the potential energy stored in a system

first law of thermodynamics in the universe, energy can neither be created nor destroyed; however, energy can change form and energy can flow from one place to another. The total energy of an isolated system remains constant

phase change a change in physical state (e.g. solid to liquid)

Internal energy

The **internal energy** (U, sometimes called the thermal energy) of a substance is the sum of the kinetic energy of its particles and the potential energy stored in their bonds and can be written as $U = KE + PE$.

$$U = E_k + E_p$$

It does not include any kinetic energy due to the bulk movement of the material, or potential energy due to external forces such as gravity. However, thermal energy is a form of energy, and as such is important to consider when applying the **first law of thermodynamics** (the conservation of energy).

If a solid body is heated, its temperature increases. The particles gain kinetic energy and, on average, vibrate faster. Therefore, as temperature increases, the amount of internal energy increases as well.

At melting point, there is a **phase change**. The kinetic energy of the particles does not change any more until the phase change is complete. The 'springs' are affected and the particles become further separated. During the phase change, the energy input is used to increase the distance between particles, not their kinetic energy. In this case, when energy is added to a substance undergoing a phase change, even though there is no increase in temperature (no increase in kinetic energy), the internal energy is still increasing because more potential energy is being stored in the bonds.

KEY FORMULA

The internal energy of a substance is equal to the sum of the potential and kinetic energy of all of its particles.

$U = E_K + E_p$

Where:

U = internal energy of a substance

E_K = total kinetic energy of the particles of a substance

E_p = total potential energy stored in the bonds of a substance

A system with internal energy can transfer heat to its environment, and may also be able to do work by applying a force to some part of its environment. The volume of an amount of gas is typically about 1500 times greater than the same amount of the liquid material. This difference in volume is used in engines to do work. For example, in a steam engine water is boiled by burning coal in a firebox inside or against a boiler. The heat from the burning coal acts to change the state of the water from liquid to gas. The pressure of the steam pushing on a piston does work on rods that connect to the wheels, and thus drive the locomotive. Hence, the internal energy of the fuel, the coal, is converted into work done on a train being pulled behind the engine. This is possible because of the change of state of the water, and the different properties of the two states.

SYLLABUS LINK

Chapter 5 discusses energy transfers by heat and work in more detail.

Temperature

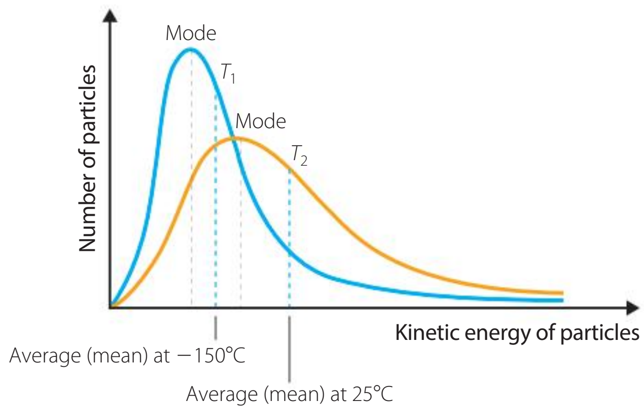
A cup of water takes a much shorter time to come to the boil (100°C) than a saucepan of water. The final temperature is the same for both, but the larger mass of water requires more heat to bring it to the same temperature, even though all the particles in the cup have, on average, the same kinetic energy as the particles in the saucepan. Thus, temperature is, to a good first approximation, a measure of the average random kinetic energy of the particles making up a body.

When a material is heated, the average kinetic energy of the particles increases. Figure 1.2.2, which is called a **Boltzmann distribution**, shows the wide range of kinetic energies of particles in the same mass of iron at two different temperatures. The peak of the curve is the most common (mode) kinetic energy of the particles.

Boltzmann distribution
a formula showing the distribution of energy among the particles of a system

When energy is added to a substance, the proportion of atoms vibrating faster increases. The average kinetic energy of particles, and therefore the temperature, increases.

FIGURE 1.2.2 The graph shows a Boltzmann distribution of the kinetic energies of the particles in a sample at two different temperatures, T_1 (–150°C) and T_2 (25°C).



Heat

heat
the transfer of thermal energy through a substance or between substances

thermal energy
heat, the form of energy that gives rise to an increase in the kinetic energy of particles

In physics, **heat** has a definite meaning that may be different from your common understanding of the term. Heat refers to energy that spontaneously moves between two substances because there is a difference in temperature between them.

When heat is added to a substance, it generally results in an increase in kinetic energy of the particles, which results in an increase in the temperature of the substance. It is important to note that heat refers to the energy that is actually being transferred, not the kinetic energy itself. Another term that can be used interchangeably with the term 'heat' is **thermal energy**.

SECTION REVIEW 1.2

REMEMBERING

1 Define the following terms.
- **a** Kinetic energy
- **b** Potential energy
- **c** Internal energy
- **d** Temperature
- **e** Heat

2 What happens to the internal energy of a substance if the average kinetic energy of its particles increases?

3 Define what happens to the internal energy of a substance if the amount of potential energy stored in its intermolecular bonds decreases.

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UNDERSTANDING

4 Determine the energy transformations that occur when the steam produced in a coal-fired power plant cause the turbines to spin.

5 Explain what happens to the potential energy of a bond if the bond is stretched or compressed away from its ideal length.

6 Compare heat and temperature.

7 Explain why an increase in the internal energy of a substance does not always result in an increase in temperature.

APPLYING

8 Construct an approximate Boltzmann distribution for the number of particles at a range of kinetic energies in a sample of water at the following temperatures.

- **a** −150°C
- **b** 25°C

9 Construct a flow diagram that shows the relationships between the concepts of kinetic energy, potential energy, internal energy, heat and temperature.

1.3 Heat transfers

Understanding heat and controlling the transfers and transformations of heat energy is vital for the survival, health and wellbeing of all living things. Humans have a unique responsibility to use that knowledge wisely.

As a society, we continue to produce and consume large amounts of energy. Much of this energy is wasted as heat that is released into the environment. This 'wasted' heat results in an increase in the overall amount of thermal energy in the global system and is a key component of **anthropogenic** climate change. In reducing the climate footprint, there is an increasing focus on the use of insulation, increasing efficiency and transitioning to renewable energy sources such as solar, wind, wave, hydro and fusion.

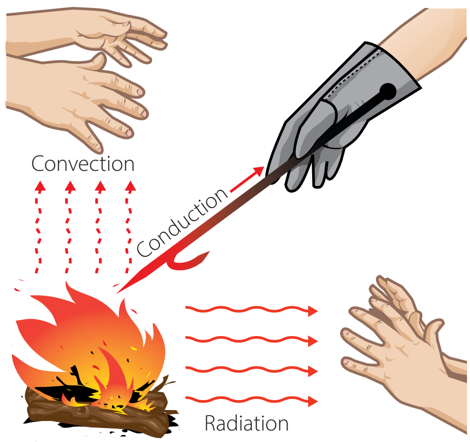

FIGURE 1.3.1 Heat can be transferred by conduction, convection and radiation.

anthropogenic human-derived; caused by human activity

Heat energy always moves from a region of high temperature to a region of low temperature. It can be transferred by conduction, convection or radiation; processes that are vital to the continued existence of life on Earth.

Conduction

Conduction is the transfer of heat energy through a substance by the action of particle collisions. When two substances of different temperature are placed in contact with each other, the particles of the hotter substance collide with those in the colder substance and transfer kinetic energy. This transfer of heat results in a decrease in the total kinetic energy of the hotter substance and an increase in the overall kinetic energy of the colder substance.

Different materials have different conducting properties. **Thermal conductivity** is a measure of how efficiently heat will flow through a substance. Solids are better **heat conductors** than liquids or gases. **Heat insulators** are poor heat conductors.

conduction the process by which energy is transferred through the collision of atoms

thermal conductivity a measure of how efficiently heat can be conducted through a material

heat conductor a material that readily allows the transfer of heat

heat insulator a material that is a poor conductor of heat

Metals

delocalised valence electrons the outer electrons of metal atoms that are free to move

Metals are particularly good heat conductors. They have large thermal conductivities. The large numbers of unattached electrons in metals are relatively free to move, and so transfer kinetic energy quickly. These **delocalised valence electrons** transfer energy to other electrons and atoms at a faster rate than electrons that are tightly bonded.

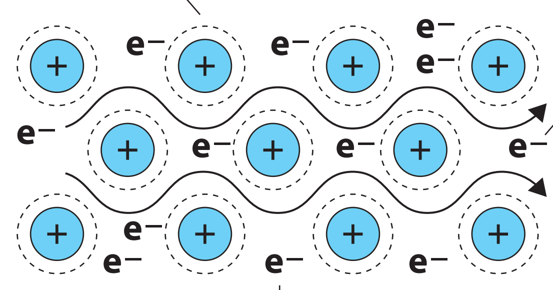

FIGURE 1.3.2 The delocalised electrons in metals are free to move and can conduct thermal energy quickly.

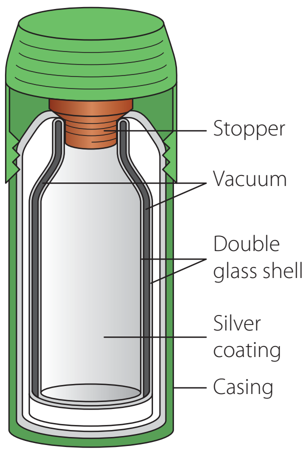

FIGURE 1.3.3 A diagram of a Dewar flask, used to store hot or cold substances

Good heat conductors, such as liquid sodium, are used in some nuclear reactors to transfer heat to water. Other good conductors are used in refrigerators, disc brakes, computer heat sinks and car engine radiators.

Almost all non-metal materials, including gases, are insulators. Unlike metals, non-metals do not have free delocalised electrons. Energy transfer occurs between relatively fixed neighbouring particles. When they are cold, birds and cats fluff their feathers and fur to trap air, which acts as an insulator. Consequently, less heat is transferred from their bodies.

Good insulators are used in house insulation, thermos (Dewar) flasks, padded jackets and duvets.

The Dewar flask

Sir James Dewar (1842–1923) designed a flask to minimise energy transfers by conduction, convection and radiation. Dewar flasks are used to store hot or cold liquids such as liquid nitrogen (boiling point 77 K) and liquid oxygen (boiling point 90 K). They have a double-walled Pyrex glass vessel with silvered walls to reflect heat. The space between the walls of the flask is evacuated. The small neck also helps reduce heat transfer.

INQUIRING FURTHER

The calorimeter is a modified version of the Dewar flask and is used in many experiments involving thermodynamics. Investigate its structure and its use.

Convection

convection process by which energy is transferred through the bulk motion of a fluid

convection current fluid circulating as a result of heating at a point or localised region; movement of fluids due to convection

Convection is the transfer of heat energy by the bulk movement of particles. The flow of particles away from a warmer to a cooler region produces a convection current. These currents result in a net flow of heat away from the warmer region to the colder region.

Convection currents only occur in fluids (liquids and gases), which have relatively weakly connected particles, and more so in gases than liquids because the particles in a gas are less tightly connected.

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In Figure 1.3.4 warm, less dense water at the bottom flows upwards, while the denser water at the top sinks. A **convection cell** is produced.

Thermal currents

Thermal currents (thermals) were first used for glider flight in 1921 by William Leusch in Germany, 20 years after the first powered flight. The pilot uses a thermal to increase altitude by flying in a spiral pattern before flying off to the next thermal. Thermals appear over towns, freshly ploughed fields, sealed roads and, occasionally, over power stations and fires.

Radiation

Radiation is the transfer of energy that does not need a medium. Unlike conduction and convection, radiation does not involve particles of matter. Except at 0K, all objects emit electromagnetic radiation (Figure 1.3.5).

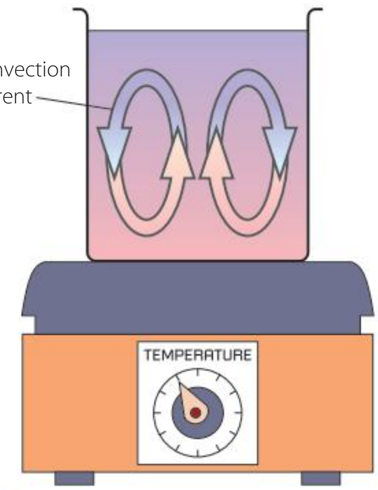


FIGURE 1.3.4 Convection currents and convection cells occur where warm and cold fluid masses intersect, for example, in the atmosphere and oceans and in hydronic home heating systems.

convection cell
the condition that occurs when there are density differences within a fluid; the density differences result in rising and falling currents

thermal currents
rising air columns of hotter air caused by the process of convection

radiation
energy transfer across space; the process by which heat is transferred without the need for a medium; energy from radioactive atoms

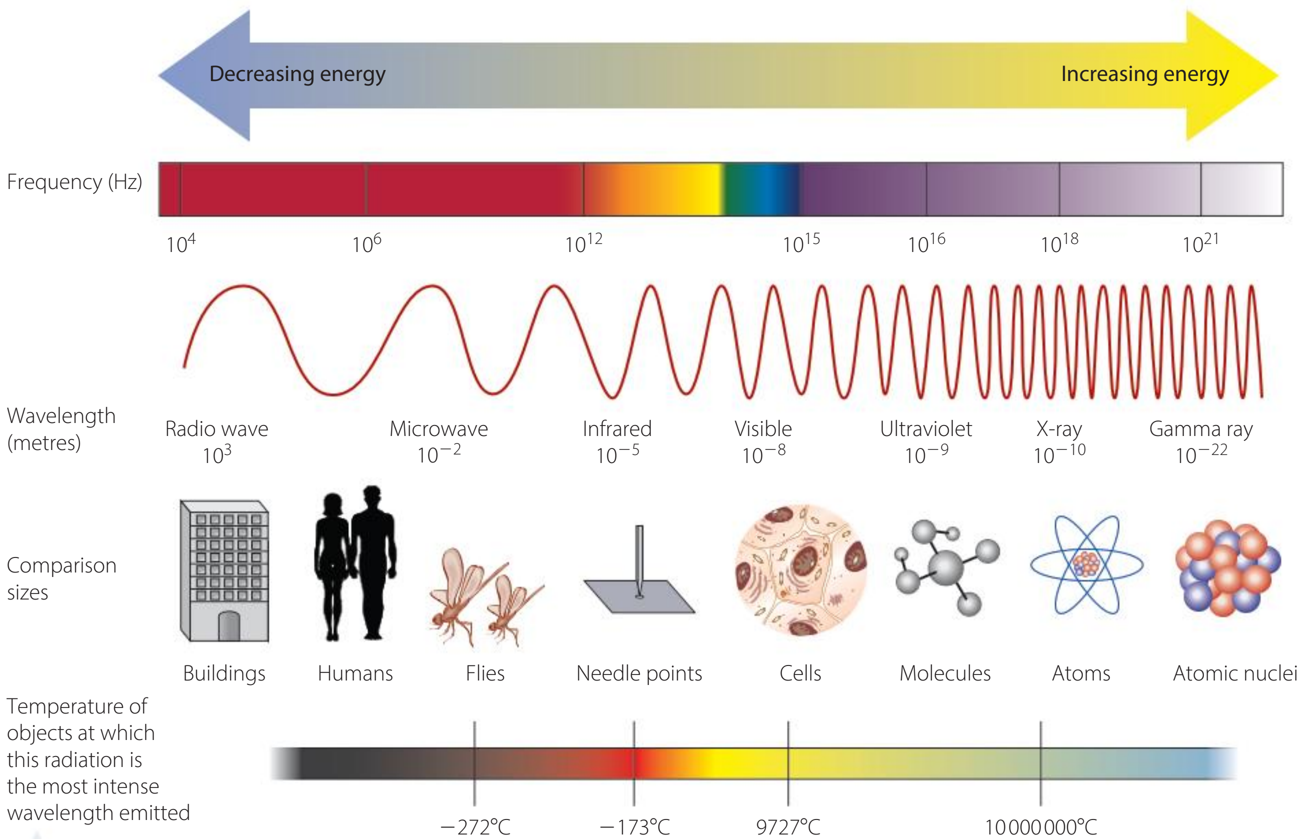
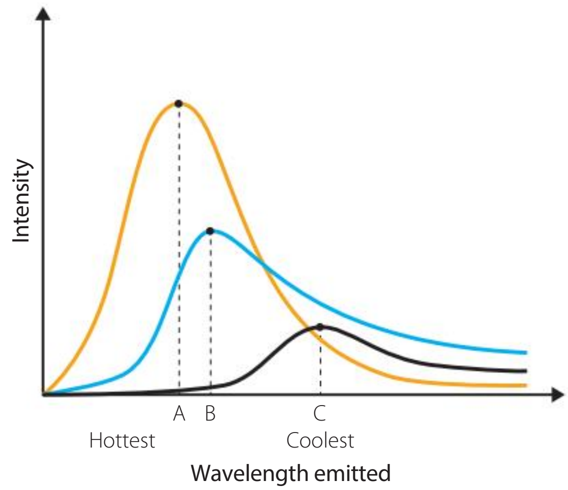


FIGURE 1.3.5 The electromagnetic spectrum

The intensity of radiation from an object clusters around a peak temperature on a Planck radiation curve such as the one shown in Figure 1.3.6. Any object with a temperature greater than absolute zero will emit electromagnetic radiation. In space, gas clouds (around 0 K) emit radio waves, stars (3000–30 000 K) emit ultraviolet and visible light. Warm bodies mostly emit infrared radiation. At about 500 K, objects glow dull red. Stars such as Spica, which mostly emit ultraviolet light, have temperatures of about 22 000 K. The radiation emitted by objects can be compared to Planck curves in order to calculate their temperature.

FIGURE 1.3.6 Planck curves showing peak intensities for three objects at different temperatures. Note that the temperature of the objects ranges from coolest on the right to hottest on the left.



1.3.1 How does heat travel?

1.3.2 Heat transfer and efficiency

When radiated energy (radiant heat) interacts with an object, some of that energy is absorbed and the rest is reflected. The fraction that is absorbed depends on the type of surface material, its texture and its colour. Black and dark-coloured surfaces absorb more radiant heat than white or light-coloured surfaces. Hence a black car gets hotter inside than a white car on a sunny day.

SECTION REVIEW 1.3

REMEMBERING

1 Define the following processes.

- **a** Conduction
- **b** Convection
- **c** Radiation

2 List the following regions of the electromagnetic spectrum in order of increasing temperature of their sources.

Infrared

X-ray

Visible

UNDERSTANDING

3 Explain why copper is a better thermal conductor than wood.

4 Explain why the temperature at the surface of a large body of water is generally warmer than the water lower down.

5 Describe the heat exchanges that occur in the process of energy being transmitted from the Sun onto the surface of the Earth and eventually into the movement of air in the form of wind.

APPLYING

6 Use your understanding of heat exchange to draw the motion of water directly above an underwater volcano.

CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 Define the following terms.
   a Matter
   b Energy
   c Atom
   b Molecule
   e Particle
   f Brownian motion
   g Kinetic energy
   h Potential energy
   i Internal energy
   j Elastic collision
   k Intermolecular force
   l Temperature
   m Heat
   n Conduction
   o Convection
   p Radiation

2 What causes the motion of particles in a substance to be completely random?

CATEGORY QUESTIONS

3 Explain the differences between heat and temperature.

4 Describe the key features of the kinetic particle model.

5 Explain the distinguishing features between matter in the solid, liquid and gaseous phases in terms of the intermolecular bonding, separation and freedom of movement of their constituent particles.

6 Use the kinetic particle model and the concept of intermolecular bonding to explain how one object can be a better conductor of heat than another.

7 Explain how scientists can use the radiation emitted by a distant source to estimate its temperature.

ELABORATION QUESTIONS

8 How does the kinetic particle model of matter give meaningful definitions to the concepts of heat and temperature, which were only loosely defined prior to the formulation of the model?

9 If particles within a substance all have varying amounts of kinetic energy and temperature is linked to kinetic energy, why don't we talk about the temperature of individual particles?

10 What would be the effect on the temperature of a substance if the collisions that were taking place between its particles were not perfectly elastic?

11 When scientist wish to cool a substance down to very low temperatures, they often use a process called evaporative cooling, which consists of the removal of the most energetic particles in the substance. Explain why this would result in a cooling of the substance.

EVIDENCE QUESTIONS

12 Research the hypothetical concept of 'caloric' as a means of energy and heat transfer, and outline the evidence, or lack of it, that supports the kinetic particle model of heat rather than the caloric.

13 If scientists had the instruments to measure and compute the paths and collisions of every individual particle in a substance, would this change the kinetic particle model? If so, how?

14 Explain how the discovery of Brownian motion supported the idea of matter being made up of atoms.

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END-OF-CHAPTER EXAM

End-of-chapter test

PHYSICS

1 If a substance is described as having a fixed shape and volume, which of the following states of matter is the substance in?

A Solid

B Liquid

C Gas

D Plasma

2 Which of the following is not an assumption of the kinetic particle model?

A All matter is made up of small particles in constant motion.

B Collisions between particles are perfectly elastic.

C Temperature is transferred through conduction.

D The motion of particles obeys classical mechanics.

3 Which of the following is an example of potential energy?

A Energy due to the motion of an object

B Energy stored by the displacement of particles

C Energy that is transferred as heat

D Energy that emits infrared radiation

4 Which of the following properties of a metal gives rise to it being described as a good heat conductor?

A Its shiny lustre

B Its malleability

C Its reactivity with acids

D Its large number of free electrons

5 Which of the following heat transfer methods would be most likely to be found in a volume of gas?

A Conduction

B Convection

C Radiation

D Condensation

6 What is the transfer of thermal energy between substances known as?

7 If the temperature of a substance is increasing, is the average kinetic energy of the particles in that substance increasing, decreasing or remaining the same?

8 What is the sum of the kinetic and potential energy in a substance referred to?

9 Which type of heat transfer heats Earth's atmosphere by the Sun?

10 What is the term for the study of energy, how it is transferred and how it affects matter?

11 Define 'Brownian motion'.

12 Describe how the addition of heat can affect a substance.

13 Explain the relationship between kinetic energy and temperature.

14 Differentiate between heat and temperature in terms of the kinetic particle model of matter.

15 Define 'heat conduction'.

16 Explain what happens to the particles of a substance when heat is added to it.

17 Explain the process of heat convection.

18 Describe the differences between solids, liquids and gases in terms of their kinetic energy, potential energy, intermolecular forces and the distance between their particles.

19 Redraw the Boltzmann distribution of kinetic energies of particles to include a third temperature of 200°C.

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2 TEMPERATURE AND SPECIFIC HEAT CAPACITY

Introduction

One of the most important and interesting processes undertaken by scientists is that of experimental investigation. Science is about discovering knowledge and processes through observation and experiment, by verifiable and reproducible means, which is what investigation is all about. This is why investigations are central to science, and why they are so much fun.

In this chapter we will investigate how to measure the temperature of an object and the relationship between temperature and applied heat. We will also examine the reason why the temperature of an object changes when heat is added.

Stimulus questions

Why is it important to have an international unit of measure?

Which has more energy – a hot cup of coffee or a cold swimming pool?

What property of water makes it ideal for use as a coolant in car engines?

Can the temperature of a solid, liquid or gas ever reach absolute zero?

How confident can you be that a measurement is correct?

2.1 Converting temperature

In common experience, the temperature of an object is a measure of how hot or cold something is. A freshly brewed cup of coffee is said to be hot and a swimming pool on a winter's day is said to be cold. These are examples of **qualitative** measurements.

The temperature of an object is directly related to the average kinetic energy of the particles making up the substance. As it is very difficult to measure the kinetic energy of these individual particles, it is important to be able to gain a **quantitative** measurement of the temperature of a substance.

qualitative
non-numerical data; descriptive information

quantitative
numerical data; specific amount

A numerical temperature scale

One way to define a numerical temperature scale is by assigning arbitrary values to two common temperatures and then creating a scale of values between them.

The scale that is in most common use today is the Celsius or centigrade scale (in a few countries the Fahrenheit scale is used). The most important scale for scientists is the absolute or Kelvin scale.

Celsius

The Celsius scale uses the boiling and freezing points of water at a standard atmospheric pressure as the fixed points that represent temperatures that are universally familiar. The Celsius scale assigns the value of 0°C ('zero degrees Celsius') to the freezing point of water and 100°C to its boiling point. The distance between these points is then broken down into 100 equal intervals marking a degree (therefore it is termed the 'centigrade' scale).

INQUIRING FURTHER

Investigate the development of the Fahrenheit temperature scale and identify why this scale is no longer used in Australia.

The Kelvin scale

The Kelvin scale was developed in the 1800s by William Thompson (also known as Lord Kelvin), who critically examined the recently discovered relationship between the volume and temperature of a gas. As a result of his investigations, he theorised that the volume of an ideal gas should become zero at a temperature of approximately −273°C. The only way that this could happen, he hypothesised, was if the kinetic energy of the particles was also zero. It is for this reason that he coined the term **absolute zero** to indicate infinitely cold.

Kelvin used absolute zero as the basis for an absolute temperature scale. Each increment on this scale is called a kelvin rather than a degree and is equal in value to one degree on the Celsius scale. When reporting the temperature in kelvin, the symbol K is used in place of the degree Celsius (°C) symbol.

Just like the Celsius scale, the boiling and freezing points of water are used to determine the range of the Kelvin scale. Water is said to freeze at 273 K (stated as '273 kelvin') and the boiling point is therefore 100 K higher at 373 K.

absolute zero
the theoretical lowest possible temperature; −273.15°C on the Celsius scale or 0 K on the absolute or Kelvin scale

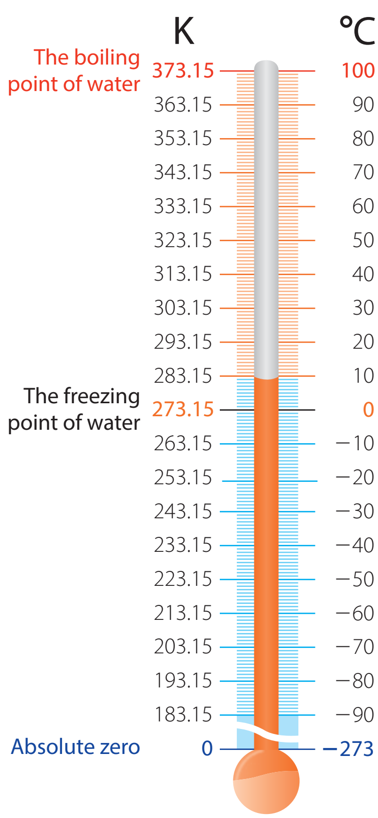

FIGURE 2.1.1 The Kelvin scale compared with the Celsius scale

KEY FORMULA

Conversion between the Kelvin (absolute) and Celsius scales

$T_K = T_C + 273$

Where:

T_K = temperature in kelvin

T_C = temperature in degrees Celsius

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WORKED EXAMPLE 2.1.1

a The highest ever recorded temperature in Queensland was measured on 12 February 2017 in Thargomindah, when the Bureau of Meteorology recorded a sweltering 47.2°C. Calculate what this temperature would be on the Kelvin scale.

ANSWER

1 Use the equation:
$T_K = T_C + 273$

2 Substitute the known values:
$T_K = 47.2 + 273$

3 Calculate the answer and use the correct units:
$T_K = 320.2\,K$

b Under standard atmospheric conditions, gaseous oxygen becomes liquid at 90 K. Calculate what this temperature would be on the Celsius scale.

ANSWER

1 Use the equation:
$T_K = T_C + 273$

2 Rearrange for the value of interest:
$T_C = T_K - 273$

3 Substitute the known values:
$T_C = 90 - 273$

4 Calculate the answer and use the correct units:
$T_C = -183°C$

The Kelvin scale is popular in scientific circles because it does not contain negative numbers and is therefore convenient for recording very low temperatures such as the point at which gases become liquid (e.g. nitrogen gas becomes liquid at –195°C or 78 K). The lack of negative numbers makes it simpler to be able to compare different temperatures.

2.1.1 Temperature conversion formulas

TABLE 2.1.1 Interesting temperatures on the Kelvin and Celsius scales

INTERESTING TEMPERATURES	TEMPERATURE	
	K	°C
Absolute zero	0	–273.15
The average temperature of space	2.725	–270.425
Helium liquefies	4	–269
Oxygen liquefies	90	–183
The lowest recorded surface air temperature on Earth (Russia's Vostok Station in Antarctica, on 21 July 1983)	184	–89
Average surface air temperature on Earth	288	15
Normal human body temperature	310	37
Highest recorded surface air temperature on Earth (Furnace Creek Ranch in Death Valley California, USA)	331	58

INTERESTING TEMPERATURES	TEMPERATURE	
	K	°C
Titanium melts	1941	1668
Temperature of the surface of the Sun	5778	5505
Temperature in the core of the Sun	15.7×10^6	15.7×10^6

Absolute zero

second law of thermodynamics the direction of heat flow is always from a hotter object to a colder object

The Kelvin scale uses absolute zero – the temperature at which the motion of particles should cease – as its reference point, but the **second law of thermodynamics** states that heat always moves from a hotter object to a colder object, so can we actually reach absolute zero?

The answer is no, because for a substance to reach the lowest of temperatures, 0 K, it would need to transfer energy to something that is colder. For this to occur, the second object would need to be below absolute zero, and we are yet to find anything that cold! In addition, the kinetic particle model states that at absolute zero there is no energy and hence no movement in any of the particles of matter even at a subatomic level. There is no evidence that such a state can exist.

SECTION REVIEW 2.1

REMEMBERING

1 Identify the lowest possible temperature on the Kelvin scale. How is this defined?

2 Why is it important to have a universal temperature scale that is used by all scientists?

UNDERSTANDING

3 Outline the advantages of using the Kelvin scale when taking measurements.

4 Classify the following measurements as qualitative or quantitative.
- a The water is warm.
- b The water is 318 K.
- c The patient has a temperature of 38.4°C.
- d The patient is running a temperature.
- e Today is hotter than 35°C.

APPLYING

5 The temperature at which most people begin to feel a burning sensation is 54°C. What is this temperature on the Kelvin scale?

6 Write an equation that allows you to convert a temperature on the Kelvin scale to a temperature on the Celsius scale.

ANALYSING

7 Explain any disadvantages there may be in using the Kelvin scale.

2.2 Collecting data

As the temperature of an object changes, so do many of its properties. Some properties change in predictable ways; for example, the volume of most objects expands when they are heated. The concrete in sidewalks changes size depending on its temperature, and it is for this reason that expansion joints are included to prevent cracking. Another property that can change is the electrical resistance of an

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electrical conductor; generally, the resistance will increase as the temperature increases because the increased vibration of the particles inhibits electrical flow.

To measure the temperature of an object quantitatively, an instrument called a **thermometer** is used. There are many different types of thermometers, but they all operate by making a measurement of some form of temperature-dependent property of the thermometer. Table 2.2.1 lists some common examples of thermometers and the properties that allow them to measure temperature.

thermometer
a device that measures temperature or a temperature gradient

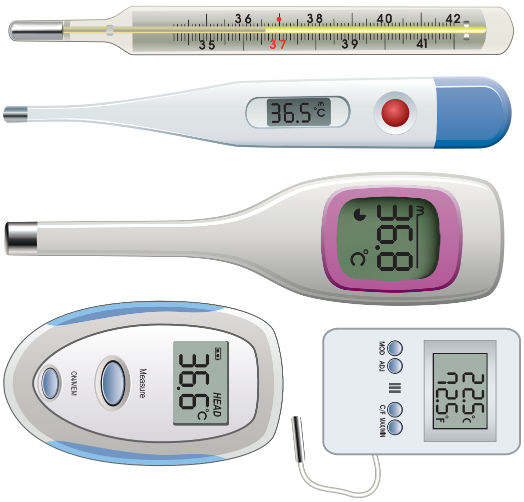
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FIGURE 2.2.1 There are many different thermometers used to measure the temperature of an object. They all measure a property of the thermometer that changes with temperature.

INQUIRING FURTHER

Investigate other ways in which thermal expansion must be considered; for example, in telephone wires, glass cookware and high-speed planes.

TABLE 2.2.1 Physical properties used by thermometers to indicate temperature change

TYPE OF THERMOMETER	DESCRIPTION
Mercury in glass	Uses different coefficients of expansion between mercury and glass
Thermocouple	Uses different temperature-dependent electrical properties of different metals that are brought into contact
Thermostat	Uses variation in electrical resistivity of a material with temperature
Thermal paint	Uses colour change with temperature
Bimetallic strip	Uses variation in coefficients of expansion between two different metals to detect temperature changes
Infrared	Uses the electromagnetic radiation radiated from a surface to measure temperature on the absolute temperature scale
Digital	Uses the variation in resistivity of a material with temperature; the greater the resistance, the lower the current

SECTION REVIEW 2.2

REMEMBERING

1 Describe a thermometer.

2 For each of the digital and thermostat thermometers listed in Table 2.2.1, identify the property that allows it to measure temperature.

UNDERSTANDING

3 Explain the key features of a thermometer that allows it to make a measurement of the temperature of an object.

ANALYSING

4 Why do railway lines have gaps between each section of line?

2.3 Practical skills: measurements

measurand
a specified quantity to be measured

measurement result
the best estimate of the 'true value' of a measurand given the limitations of the actual measurement device used

true value
for continuous variables, this is an unknowable, ideal value that represents the measurand

accurate
the degree to which a measurement correctly reflects or approaches the true value

precise
the degree to which the individual measurements cluster around their mean value

uncertainty
estimate of the range of values within which the true value of a measurement or derived quantity lies

When scientists take measurements, they are comparing the **measurand** to some known quantity that is represented in an appropriate scale of units on the measuring device. When they collect data, they are measuring how many units are present of some property of interest. This is called the **measurement result**. We may also expect there to be a '**true value**', an exact number that represents what we are measuring. This cannot, however, be known with 100% certainty. For the collected data to be as valid as possible – that is, the best possible estimate of the true value – the measurement result should be both **accurate** and **precise**. However, there will always be some **uncertainty** in any measurement.

When a measurement is taken and recorded, it is vital that three aspects of the quantity are clearly specified to ensure the data are clearly communicated: the measurement result, the uncertainty in the measurement result and the units.

KEY FORMULA

The three aspects required when reporting a measurement

Measurement = (measurement result ± the uncertainty in the measurement result) units

Measurement result

indication value
single result of a measurement

mean value
the average value of a set of indication values

The measurement result is the best estimate of the true value. Except for discrete, countable things, the true value is an ideal that can never be completely and unambiguously known. It is logically impossible to know the exact value of a continuous variable, even for standard values such as the speed of light, because the measurement obtained will always be limited by the accuracy of the measuring device.

Every measurement provides an indication of the true value. Taking repeated measurements provides a spread of **indication values** or results, and the **mean value** of these should be a very good estimate of the true value. Notice this is an agreed procedure. We agree that the mean is the most likely or best estimate of the true value. It is not certain that it is the true value. A plot of the number of indication values versus reading shows the spread of results around the supposed true value.

KEY FORMULA

Calculating the mean measurement result from individual measurement results

$$\text{Mean} = \frac{\text{the sum of the indication values}}{\text{the number of measurements}}$$

Accuracy

An accurate measurement result is one that represents the true value of the measurand as closely as possible. Even when the true value is unknown, scientists can rely on the best available **accepted value** to compare with the experimental measurement result to determine its accuracy.

The mean measurement result may be close to the true or accepted value, as shown in Figure 2.3.1 parts (a) and (b); these results would be considered accurate.

Alternatively, the mean measurement result may cluster around another value that is not the true value such as in Figure 2.3.1 parts (c) and (d); these would be considered 'inaccurate'.

accepted value
the value of a substance or quantity that is universally agreed as being a best estimate due to multiple and highly accurate measurements

Precision

Precision relates to the skill of the experimenter within the environment and the quality of both the equipment and the measuring techniques used. If the quality of these is high, the measurement result is more precise; if the quality is low, the result is imprecise. Precise measurements are shown in Figure 2.3.1 parts (a) and (c), as the individual indication values cluster closely around the mean; whereas Figure 2.3.1 parts (b) and (d) show imprecise measurement results because the individual indication values spread significantly around the mean.

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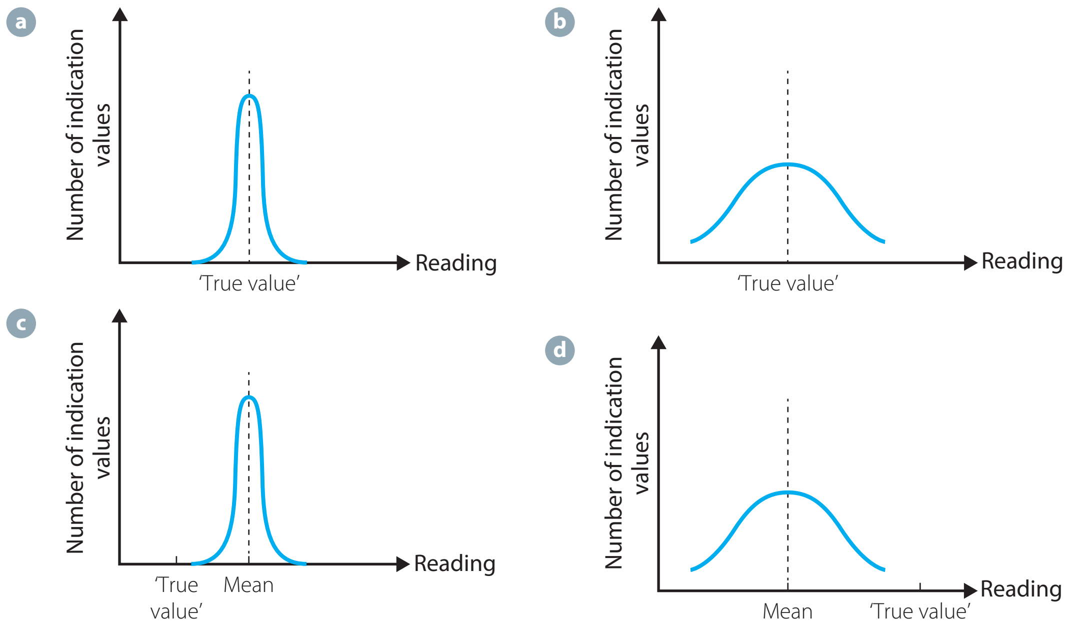

FIGURE 2.3.1 In a plot of indication values versus reading, results can be: **(a)** accurate and precise, **(b)** accurate and imprecise, **(c)** inaccurate and precise or **(d)** inaccurate and imprecise.

Standard or scientific form

When reporting the measurement result, it is possible to use regular decimal notation or the scientific form for numbers. The scientific form enables very large and very small numbers to be expressed relatively simply. Numbers are written as a number between 1.0 and 10 multiplied by the relevant power of 10. For example:

The distance from Earth to the Sun is 150 000 000 km. In scientific form this is written as 1.5×10^8 km.

The average distance between two atoms is 0.000 000 000 16 m. In scientific form this is written as 1.6×10^{-10} m.

As a rule, it is not usual to express the numbers between 0.01 and 1000 in scientific form; it is not wrong to do it, it is just not the preferred method.

Uncertainty

No measurement is exact. There are always effects that contribute to each measurement of a quantity being a bit different. They add to the uncertainty with which an indication value or measurement result can be reported.

Good experimental observers always ensure that they can estimate the uncertainty, which states the range of values between which they are confident the true value lies. In Figure 2.3.1, parts (a) and (b) both show the dispersion of indication values around the true value. This dispersion is the result of random effects such as small air currents or localised temperature changes.

This dispersion of indication values is called **random error**, although this term is starting to be replaced by more precise concepts. The term 'random error' alerts us to the possibility that, if the dispersion of the results is not considered, a mistake will be made in reporting the value correctly.

It is not possible, in principle, to predict the next indication value from the previous measurement. If it were, the effect could be considered in making the estimate of the true value. Figure 2.3.1 parts (c) and (d) show the mean of the indication values, which are offset from the true value. Some of this offset can be accounted for by careful consideration of the situation and the measurement activities. These **systematic errors** can be identified and indication values adjusted for these known, regular effects.

The uncertainty in a measurement is a quantity that makes apparent the quality of the measurement. The uncertainty represents a careful estimate of doubt about the value. Uncertainty should not be referred to as an error, as an error is a mistake and no mistake should be made in measurement.

random error
a variation that affects a measurement in a random way so that successive measured values may reflect small changes from each other

systematic error
an error that acts in a predictable manner to give a consistent offset in data

absolute uncertainty
the size of the range of values in which the true value of a measurement probably lies

parallax error
error in a measurement caused by the change in the apparent position of an object viewed from two different lines of sight

confidence interval
a range of values in which an indication value lies

maximum value
upper limit of a confidence interval

minimum value
lower limit of a confidence interval

range
the difference between the maximum and minimum values of a measured confidence interval

There are several conventions used when reporting uncertainty, including absolute uncertainty, relative uncertainty, proportional error and the use of significant digits.

Absolute uncertainty of single measurements

There is no set way to determine the amount of uncertainty in a measurement and it is left to the observer to calculate. One of the ways that uncertainty can be reported is using **absolute uncertainty**.

For example, imagine that a student is trying to measure the diameter of a tennis ball using a metre ruler. The two limiting factors in trying to determine the indication result in this case are the size of the minimum graduations on the metre ruler and **parallax error**.

The experimenter might decide that they are confident that the diameter of the tennis ball lies somewhere between 6.7 and 6.8 cm. We term this range of indication values the **confidence interval**.

The **maximum value** is the upper limit of a confidence interval and the **minimum value** is the lower limit of a confidence interval.

In this case, the maximum value would be 6.8 cm and the minimum value would be 6.7 cm.

The difference between the maximum and minimum values is termed the **range** and is found by subtracting the minimum value from the maximum value.

In the tennis ball experiment, the range would be 0.1 cm (6.8 cm–6.7 cm).

We can then determine the indication value of the measurement by calculating the halfway point of the range.

The indication value for the tennis ball would be 6.75 cm (6.7 cm + 0.05 cm).

The absolute uncertainty in the indication value is calculated as one half of the range.

The absolute uncertainty in the tennis ball is therefore 0.05 cm.

To correctly report the measurement, we would have to state the indication value and the absolute uncertainty.

The diameter of the tennis ball as measured with the metre ruler would be 6.75 ± 0.05 cm.

KEY FORMULA

Calculating the range of a single measurement

Range = maximum value – minimum value

KEY FORMULA

Calculating the indication value of a single measurement

Indication value

$$= \text{minimum value} + \frac{1}{2}\text{range}$$

KEY FORMULA

Calculating the absolute uncertainty in a single measurement

$$\text{Absolute uncertainty} = \frac{1}{2}\text{range}$$

KEY FORMULA

Reporting a single measurement with absolute uncertainty

Measurement

= indication value ± absolute uncertainty

Absolute uncertainty of repeated measurements

As discussed previously, when repeat measurements are taken, the measurement result is simply the average of the individual indication values. The way in which the absolute uncertainty is calculated is dependent upon whether you are dealing with a small data set (less than 10 indication values) or a large data set (greater than 10 indication values).

For a small data set, the minimum value is the smallest individual indication value and the maximum value is the largest individual indication value.

The absolute uncertainty can be calculated in a similar manner to that for a single measurement.

For example, let's say another student wanted to measure the diameter of a tennis ball, this time using a Vernier calliper. This time the error was not due to parallax, but rather due to an uncertainty as to where the ball started and ended because of its fuzziness.

The student took the following measurements:

6.721 cm, 6.731 cm, 6.695 cm, 6.748 cm and 6.712 cm

The measurement result then would be the average of the five indication values:

$$\text{Measurement result} = \frac{6.721 + 6.731 + 6.695 + 6.748 + 6.712}{5} = 6.7214 \text{ cm}$$

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The convention for the number of numerals to report in a measurement result is discussed below in the section on significant digits, but in this case it should be rounded to 6.721 cm.

The maximum value in this data set is 6.748 cm and the minimum value is 6.695 cm, so the absolute uncertainty then is:

$$
\begin{aligned}
\text{Absolute uncertainty} &= \frac{1}{2}\text{range} \\
&= \frac{1}{2}(\text{maximum value} - \text{minimum value}) \\
&= \frac{1}{2}(6.748 - 6.695) \\
&= 0.0265
\end{aligned}
$$

The convention for the number of numerals to report in the absolute uncertainty is one or at most two numerals. In this case the uncertainty would be given as 0.03 cm.

To report the final measurement result, include both the measurement result and the absolute uncertainty.

In the example, the final measurement result for the diameter of a tennis ball as measured with a Vernier calliper would be 6.72 ± 0.03 cm.

In the case of more than 10 indication values, the absolute uncertainty is equal to the standard deviation of the data set. Most graphical calculators and spreadsheet software have in-built statistical functions that will easily calculate these values.

Significant figures

Place value is used to report the precision of a measurement. For (2.5 ± 0.1) cm, the final place in the value, the 5 in the tenths column for 2.5, is uncertain by 0.1 cm. We are saying, 'The best estimate of the value is 2.5 cm, and we are confident the true value lies between 2.4 cm and 2.6 cm'. Similarly, for the more accurate and precise measurement (2.513 ± 0.001) cm, we are reporting confidence that the true value lies between 2.512 and 2.514. The measurement is uncertain in the thousandths column.

The number of **significant figures** in a measurement can be found by counting the number of reported digits. There are rules for deciding on the number of significant figures in a reported value:

1. Zeros in front of the integer part of a numeral are not significant; for example, 00346 has three significant figures.
2. All non-zero figures are significant; for example, in 25.4 there are three significant figures.
3. All zeros between non-zero digits are significant; for example, in 203.4 and 27.6002 the zeros are significant. The numbers have four and six significant figures respectively.
4. All zeros to the right of a decimal point, which follow a non-zero digit, are significant; for example, in 21.000 the zeros are significant (five significant figures).
5. For numbers less than 1, the zeros before the first non-zero digit are not significant, for example, 0.003682 has four significant figures, starting at the digit 3.

Numbers between zero and 0.01 and numbers between 10 and 1000 are not usually written in standard form. Between 10 and 1000, a zero in the units' column is then treated as significant. Thus, 200 and 850 both have three significant figures.

Other than 100–1000, a number such as 350000 has two significant figures, because it can be written as 3.5×10^5; however, if written as 3.50000×10^5 it has six significant figures.

significant figure
digit reported in a measurement result; the number of significant figures is the number of meaningful digits in a measurement result

percentage uncertainty
a measure of the uncertainty of a measurement compared with the size of the measurement, given as a percentage

relative uncertainty
a measure of the uncertainty of a measurement as a fraction of the measurement result

Relative and percentage uncertainty

Uncertainties can also be given as relative or percentage uncertainty, which allow us to compare different data sets to see which is the more accurate. **Percentage uncertainty** is calculated by finding the **relative uncertainty**, then converting it to an equivalent fraction out of 100.

KEY FORMULA

Calculating relative uncertainty

$$\text{Relative uncertainty} = \frac{\text{absolute uncertainty}}{\text{measurement value}}$$

> **KEY FORMULA**
>
> Calculating percentage uncertainty
>
> $$\text{Percentage uncertainty} = \frac{\text{absolute uncertainty}}{\text{measurement value}} \times 100\%$$

Relative and percentage uncertainties are usually given to two significant figures with no units because they are the ratio of the absolute uncertainty in the measurement. The absolute uncertainty and the measurement have the same units, so when you divide one by the other, the units cancel out.

The percentage uncertainty in the tennis ball diameter measured using the metre ruler would be calculated as:

$$\text{Percentage uncertainty} = \frac{0.05}{6.75} \times 100\% = 0.74\%$$

So, the diameter of the tennis ball would then be reported as:

$$6.75 \pm 0.74\%$$

WORKED EXAMPLE 2.3.1

Calculate the relative and percentage uncertainties for these values:

a 2.5 ± 0.1 cm

b 2.513 ± 0.001 cm

ANSWERS

a **1** State the equation:

$$\text{Relative uncertainty} = \frac{\text{absolute uncertainty}}{\text{measurement value}}$$

2 Substitute the known values:

$$\text{Relative uncertainty} = \frac{0.1\text{ cm}}{2.5\text{ cm}} = 0.04$$

3 State the equation:

$$\text{Percentage uncertainty} = \frac{\text{absolute uncertainty}}{\text{measurement value}} \times 100\%$$

4 Substitute the known values:

$$\text{Percentage uncertainty} = \frac{0.1\text{ cm}}{2.5\text{ cm}} \times 100\% = 4\%$$

b **1** Substitute the known values into the appropriate equation:

$$\text{Relative uncertainty} = \frac{0.001\text{ cm}}{2.513\text{ cm}} = 0.000\,40$$

2 Substitute the known values into the appropriate equation:

$$\text{Percentage uncertainty} = \frac{0.001\text{ cm}}{2.513\text{ cm}} \times 100\% = 0.040\%$$

Proportional error

Some measurements, called physical constants, are extremely precise; these accepted values can be considered *as though* they are true values. For example, the charge on an electron is $1.602\,176\,565 \times 10^{-19}$ C. The absolute uncertainty in this measurement is $\pm 0.000\,000\,035 \times 10^{-19}$ C. The relative uncertainty is an incredibly precise 2.2×10^{-8}.

> **KEY FORMULA**
>
> $$\text{Proportional error} = \left| \frac{\text{measurement result} - \text{accepted value}}{\text{accepted value}} \right|$$

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When a measurement is made on a property that has a commonly accepted constant value, the degree of precision of the measurement can be shown using **proportional error**. This is the difference between a measurement result and an accepted value, expressed as a fraction of the accepted value.

Percentage error is the ratio of the magnitude of the proportional difference between an accepted value and a measurement result, expressed as a percentage:

proportional error the difference between a measurement result and an accepted value, expressed as a fraction of the accepted value

percentage error the difference between a measurement result and an accepted value, expressed as a percentage of the accepted value

KEY FORMULA

Calculating percentage error

$$\text{Percentage error} = \left|\frac{\text{measurement result} - \text{accepted value}}{\text{accepted value}}\right| \times 100\%$$

Proportional error and percentage error are useful for helping you compare your accuracy with far more precisely measured quantities; however, neither is defined in the international measurement standards from the Bureau International des Poids et Mesures (BIPM).

WORKED EXAMPLE 2.3.2

A manufacturer gives the wavelength of light as $(671 \pm 5) \times 10^{-9}$ m. A student measured the wavelength to be $(660 \pm 9) \times 10^{-9}$ m.

a Does the student's measurement result fit within the accepted value of the measurement result?

b Calculate the percentage error in the student's measurement result.

ANSWERS

a The range of the manufacturer's measurement result is 666×10^{-9} m to 676×10^{-9} m.

The range of the student's measurement result is 651×10^{-9} m to 669×10^{-9} m.

1 Identify the overlap:

The two ranges overlap in the range of 666×10^{-9} m to 669×10^{-9} m.

2 Label the horizontal axis and mark the correct overlap values:

This can be visualised with the diagram in Figure 2.3.2.

FIGURE 2.3.2 Overlap in measurement results for manufacturer's accepted value and student measurement result

b
$$\text{Percentage error} = \left|\frac{\text{measurement result} - \text{accepted value}}{\text{accepted value}}\right| \times 100\%$$

$$= \left|\frac{660 \times 10^{-9}\ \text{m} - 671 \times 10^{-9}\ \text{m}}{671 \times 10^{-9}\ \text{m}}\right| \times 100\%$$

$$= 1.6\%$$

Units

When taking a measurement of some property, a scientist is measuring how many of some standard unit are present on the measuring device. For example, when measuring the diameter of a tennis ball, the diameter is being compared to the cm on the metre ruler.

As measurements often need to be communicated across international boundaries and may need to be repeated by different experimenters, it is important that there is a common set of standard units that have a universally accepted value. The set of standards that is accepted in science is the Système Internationale or **SI system**. It provides definitions of quantities, lists the most up-to-date values for important quantities, codifies measurement theory and practice, and provides standards for the reporting of measurements. No country uses only SI units. If it did, it would use kiloseconds instead of hours.

SI system
the modern form of the metric system that stipulates the true values of units

2.3.1 BIPM

Fundamental units

Seven units are defined for the fundamental or basic quantities – length, mass, time, current, temperature, luminous intensity and amount of substance. These units are shown in Table 2.3.1.

TABLE 2.3.1 The fundamental or basic SI units and their definitions

Length	The unit of length is the metre (m), which is defined as 1 650 763.73 wavelengths of the orange-red line of the spectrum of ^{86}Kr (krypton) in a vacuum.
Mass	The unit of mass is the kilogram (kg), which is based on a cylinder of platinum–iridium alloy kept by BIPM in Paris.
Time	The unit of time is the second (s), which is defined as the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the ^{133}Cs (caesium) atom at 0 K.
Electric current	The unit of current is the ampere (A), and this is defined as the current that, if maintained in two straight parallel conductors of infinite length and negligible cross-section, separated from each other by a distance of 1 m in a vacuum, will produce a force equal to 2×10^{-7} newton per metre of length between the conductors.
Temperature	The unit of temperature is the kelvin (K), which is defined as $\frac{1}{273.16}$ of the thermodynamic temperature of the triple point of water.
Luminous intensity	The unit of luminous intensity is the candela (cd), which is defined as the luminous intensity in the perpendicular direction of a surface of $\frac{1}{600000}$ square metre of a black body at the freezing temperature of platinum (2042 K) under a pressure of 101 325 pascals.
Amount of substance	The unit of amount of substance is the mole (mol), which is defined as the amount of substance of a system that contains as many elementary entities as there are atoms in 0.012 kilogram of carbon-12. (This number is approximately 6.023×10^{-3}.)

Derived units

Derived units are formed by combinations of the fundamental units. A simple example is the unit for area, the square metre (m^2). Other examples are:

volume – cubic metre (m^3)

speed – metre per second ($m\,s^{-1}$)

density – kilogram per cubic metre ($kg\,m^{-3}$)

A number of derived units have been given special names to commemorate notable scientists. These include frequency (hertz, Hz), force (newton, N), work and energy (joule, J), power (watt, W) and current (ampere, A).

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Prefixes

Consider the measurement of length. The metre is too large a unit with which to measure the thickness of this page. It is too small a unit to measure the distance to the Moon. For this reason, multiple or submultiple units may be formed by adding a prefix to the SI unit. The prefix is combined with the unit name and is written as one word.

TABLE 2.3.2 Common unit conversions

millimetre (mm) equal to 10^{-3} m	megawatt (MW) equal to 10^{6} W
centimetre (cm) equal to 10^{-2} m	kilogram (kg) equal to 10^{3} g
kilometre (km) equal to 10^{3} m	gigajoule (GJ) equal to 10^{9} J

The preferred prefixes relate to the SI units usually by powers of three. The common prefixes are given in Table 2.3.3.

TABLE 2.3.3 Common prefixes

MULTIPLE	PREFIX	SYMBOL	MULTIPLE	PREFIX	SYMBOL
10^{18}	exa	E	10^{-2}	centi	c
10^{15}	peta	P	10^{-3}	milli	m
10^{12}	tera	T	10^{-6}	micro	μ
10^{9}	giga	G	10^{-9}	nano	n
10^{6}	mega	M	10^{-12}	pico	p
10^{3}	kilo	k	10^{-15}	femto	f

Dimensions

In the SI system, the unit of speed is the metre per second. The quantity length per time is called the dimension of the property speed.

The dimensions of a physical quantity are written using the symbols [L], [M], [T] and [I] to represent the dimensions of length, mass, time and current, respectively. Hence, we can write:

$$[\text{speed}] = [\text{length}]\,[\text{time}]^{-1} = [\text{L}]\,[\text{T}]^{-1}$$

where the brackets are read as 'dimensions of'.

The units of all derived quantities can be found by substituting the fundamental unit for each dimension in the dimension equation. For example, in the SI system the unit of mass is the kilogram (kg) and the unit of length is the metre (m). The unit of density – dimension $[\text{M}]\,[\text{L}]^{-3}$ – then becomes $\text{kg}\,\text{m}^{-3}$ in the SI system, but $\text{lb}\,\text{ft}^{-3}$ in the British Imperial System.

The examination of the dimensions of an expression can be used to check whether an equation is likely to be correct. The dimensions of both the left-hand side and right-hand side of all equations must be dimensionally correct and equal, so that they balance. If they are not, *then the equation cannot be correct*. For example, the circumference of a circle, $C = 2\pi r$, has dimensions of length [L] on both sides: [circumference] = [L], $[2\pi r]$ = [radius] = [L] – the constant, 2π has no dimensions. Hence, the equation is dimensionally correct. Note, however, that the equations $C = 2r$ and $C = \pi r$ are also dimensionally correct, but are in fact wrong. The dimension check will only tell us if the dimensions in the equation are wrong – not that the equation is necessarily correct.

PRACTICAL ACTIVITY 2.3.1

Accuracy and precision of thermometers

MATERIALS

- a collection of different thermometers (alcohol thermometer, probe thermometer, infrared thermometer etc.)
- styrofoam cup
- glass beaker
- water
- boiling chips
- crushed ice
- Bunsen burner
- tripod
- heating mat
- retort stand
- barometer

PROCEDURE

PART A: THERMOMETER IDENTIFICATION

1. If possible, note the manufacturer, serial number and manufacturer date of each thermometer. Record this in a table like the data table for part A on the next page.
2. Record the temperature range of the thermometer.
3. Record the type of thermometer.
4. Find the precision of the thermometer either by looking at the intervals marked or by looking at the specifications of the thermometer.

PART B: CALIBRATION AT THE ICE POINT OF WATER

1. Fill a Styrofoam cup with crushed ice.
2. Add enough pre-cooled distilled water to cover the ice, but not enough so that the ice floats.
3. Thoroughly stir the ice–water mixture for a period of approximately one minute.
4. Secure the thermometer to the retort stand so that it is properly inserted into the ice–water mixture.
5. Allow the temperature of the thermometer to stabilise and record the result in a table like the data table for part B on the next page.
6. Repeat steps 1–5 for each thermometer.

PART C: CALIBRATION AT THE BOILING POINT OF WATER

1. Set up the beaker on the tripod with the Bunsen burner beneath it.
2. Half-fill the beaker with water and add a few boiling chips.
3. Secure the thermometer to the retort stand so that it is properly inserted into the water.
4. Light the Bunsen burner and allow the water to come to its boiling point.
5. Allow the temperature on the thermometer to stabilise and record the result in a table like the data table for part C on the next page.
6. Repeat steps 1–5 for each thermometer.
7. Record the atmospheric pressure in the room in which you are experimenting.

»

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WHAT ARE THE RISKS IN DOING THIS ACTIVITY?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
Heating equipment can cause burns.	Avoid touching the equipment. Wait for the equipment to cool before you put it away.
Hot water can scald.	Wear safety glasses. Avoid spilling or splashing boiling water.

RISK ASSESSMENT

RESULTS

Data table for Part A

THERMOMETER DATA	THERMOMETER 1	THERMOMETER 2	THERMOMETER 3	THERMOMETER 4
Manufacturer				
Serial number				
Date of manufacturer				
Range				
Type				
Precision				

Data table for Part B

THERMOMETER DATA	THERMOMETER 1	THERMOMETER 2	THERMOMETER 3	THERMOMETER 4
Ice point temperature (°C)				
Uncertainty (°C)				

Data table for Part C

THERMOMETER DATA	THERMOMETER 1	THERMOMETER 2	THERMOMETER 3	THERMOMETER 4
Boiling point temperature (°C)				
Uncertainty				
Atmospheric pressure (mm Hg)				

ANALYSIS OF RESULTS

1 Report the ice point temperature for each thermometer, including the absolute uncertainty and the percentage uncertainty.

2 Calculate the relative error in the ice point measurement of each thermometer, if the ice point occurs at 0.0°C.

3 Report the boiling point temperature for each thermometer, including the absolute uncertainty and the percentage uncertainty.

4 Calculate the relative error in the boiling point measurement of each thermometer, if the boiling point occurs at the temperature associated with the measured atmospheric pressure as given in Table 2.3.4 (page 36).

»

TABLE 2.3.4 Relationship between the boiling point of water and atmospheric pressure

ATMOSPHERIC PRESSURE (MM HG)	BOILING POINT OF WATER (°C)
760	99.996
750	99.629
740	99.257
730	98.880
720	98.499
710	98.112
700	97.720
690	97.323
680	96.921
670	96.512
660	96.098
650	95.676
640	95.249
630	94.814
620	94.371
610	93.921
600	93.463

DISCUSSION

1. For which of the thermometers did the ice point of water lie within the range of measurements?
2. For which of the thermometers did the boiling of water lie within the range of measurements?
3. Rank the thermometers in order of decreasing precision.
4. Which of the thermometers would you choose to use if an experiment asked you to repeat the above measurements? Why?
5. Tap water commonly contains dissolved salts. What effect will this have on the freezing point of water? What type of error will this result in?
6. What effect would wetting the stem of the thermometers have on the measured results? What type of error would this result in?

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2.4 Changes in temperature

It is common knowledge that an increase in temperature requires an addition of heat. But the exact mechanics of how this takes place requires an understanding of the kinetic particle model.

In the 18th century, heat flow was considered to be a movement of a fluid called the 'caloric'. This fluid has never been detected and we now consider heat to be a transfer of energy. A common unit still in use today to measure heat is the **calorie** (cal), which is the amount of heat energy required to raise the temperature of 1 g of water by 1° Celsius. It is equivalent to 4.186 J.

The modern understanding of temperature change is that as heat is added to a substance, it increases its internal energy. If this change in internal energy is due to an increase in kinetic energy (remembering that internal energy is the sum of kinetic and potential energy), there will be a resulting increase in temperature. This is because the temperature of an object is proportional to the average kinetic energy of the particles in that object.

Added heat will initially increase the kinetic energy of particles in contact with the heat source through the process of conduction. This will result in an immediate increase in the average kinetic energy of the entire object.

These particles then go on to elastically collide with their neighbouring particles and will transfer some of their kinetic energy in the process. This results in a decrease in the kinetic energy of the original particles, which may subsequently come in contact again with the heat source and once again gain kinetic energy. As a result of the collision, the neighbouring particles that gained kinetic energy may then go on to elastically collide with their neighbouring particles or indeed with the original particles again. In this way heat will flow or undergo **diffusion** throughout an entire object very quickly.

The speed of this process is dependent upon the thermal conductivity of the substance, and it will continue as long as the heat source is present or until a phase change temperature is approached.

When the temperature of an object is reduced, the particles in direct contact with a colder object lose kinetic energy through conduction. As each collision transfers energy from one particle to another, the particles in contact with the colder object are steadily losing energy, the average kinetic energy and hence the temperature of the overall substance will decrease.

SYLLABUS LINK

Chapter 1 discusses the kinetic particle model.

calorie
the amount of heat energy required to raise the temperature of 1 g of water by 1°C; 1 cal = 4.186 J

diffusion
the spontaneous movement of substances or energies from areas of high concentration to areas of low concentration

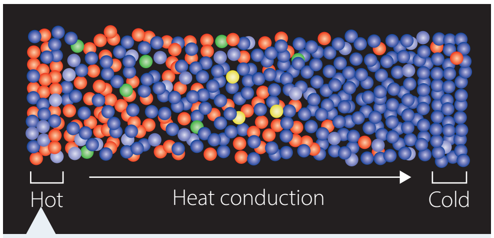

FIGURE 2.4.1 An image representing the kinetic energy of individual particles in a liquid as heat is conducted through it from a heat source on the left. Particles in red have a higher kinetic energy than particles in blue.

SECTION REVIEW 2.4

REMEMBERING

1. List the two common units of heat. Which one of these is the SI unit?
2. Define 'heat'.

UNDERSTANDING

3. When a heat source warms an object, does temperature flow between them?
4. Explain what is happening on a particle level, when a bar heater is used to warm up a room.
5. Explain on a particle level what is happening when an air conditioner is used to cool down a room.

APPLYING

6. Calculate how many joules of energy are in 150 calories.
7. Calculate how many calories are in 1400 J.
8. If a 200 W heating filament is placed in water for 2.0 minutes, how much heat is transferred to the water?

2.5 Specific heat capacity and proportionality

If heat flows into an object, its temperature will rise (as long as it is not undergoing a phase change).

Early experimenters discovered that the amount of heat Q required to change the temperature of a substance is proportional to the mass m of the substance and to the temperature change ΔT that the substance goes through. This can be neatly described by the equation below, where c is a material-specific quantity called its specific heat capacity.

KEY FORMULA

The specific heat formula

$Q = mc\Delta T$

Where:

Q = the amount of heat added to or removed from the substance

m = the mass of the substance expressed in kg

ΔT = the change in temperature expressed in °C or K

c = the specific heat capacity of the substance

specific heat capacity the amount of energy required to increase the temperature of 1 kg by 1°C (or kelvin) of a substance without a change of phase; unit: $\text{J kg}^{-1}\text{K}^{-1}$ or $\text{J kg}^{-1}\,°\text{C}^{-1}$

The **specific heat capacity** of a substance is a measure of the amount of energy required to raise the temperature of 1 kg of that substance by 1°C. This is a physical property of the material and is related to its structure. As $c = \frac{Q}{m\Delta T}$, it has units of $\text{J kg}^{-1}\text{K}^{-1}$.

Water has a high specific heat capacity. Cooking oil has a much lower specific heat capacity. Oil heats up and cools down almost twice as quickly as water. Table 2.5.1 gives the specific heat capacities of some common substances.

TABLE 2.5.1 Specific heat capacities of some common substances

SUBSTANCE	SPECIFIC HEAT CAPACITY ($\text{J KG}^{-1}\text{K}^{-1}$)
Water	4180
Ethylene glycol (antifreeze)	2400
Cooking oil	2800
Ice	2100
Steam	2000
Air	1000
Aluminium	900
Soil	800
Crown glass	670
Iron	450
Copper	380
Lead	130

Investigating specific heat capacity

A student completed an investigation by heating 1 kg of an unknown liquid by adding heat energy to it at a steady rate of $150\,\text{J s}^{-1}$ for 210 s. The temperature was measured at regular intervals during the heating process and the data recorded were plotted as shown in Figure 2.5.1.

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The graph shows that the temperature T of a body (the **independent variable**) goes up in direct proportion to the amount of heat energy Q (the **dependent variable**) put into the liquid: $\Delta T \propto Q$.

The experiment was then repeated using only 0.5 kg of the unknown liquid. All other conditions were kept the same as in the first experiment. The data were recorded and plotted as shown in Figure 2.5.2.

The second graph shows that for the same energy input, *half* the mass increases its temperature (the independent variable) by *twice* as much. Therefore, the change in the temperature of the body is inversely proportional to the mass of the body (a dependent variable):

$$\Delta T \propto \frac{1}{m}$$

Putting these two findings together gives us the relationship:

$$\Delta T \propto \frac{Q}{m}$$

There is always a constant, c, that makes a proportionality an equality, so by rearranging you get:

$$c\Delta T = \frac{Q}{m}$$

$$c = \frac{Q}{m\Delta T}$$

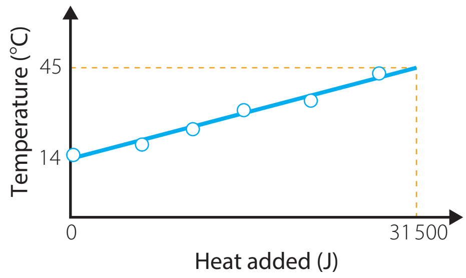

FIGURE 2.5.1 The graph shows that the change in temperature of the liquid is directly proportional to the amount of energy put in.

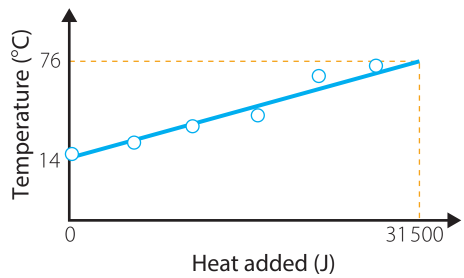

FIGURE 2.5.2 The graph shows that for the same energy input into half the mass, the temperature increase is doubled.

independent variable
a variable upon which another variable is dependent; also called the controlled variable

dependent variable
the variable that changes as a result of a change in the independent or controlled variable

The constant c is the specific heat capacity of the substance that is being heated; Q is the quantity of energy supplied; m is the mass of the body being heated and ΔT is the change in temperature. The units of the specific heat capacity can be found by substitution of the units into the last formula:

$$\text{Units of } c = \frac{\text{J}}{\text{kg K}} = \text{J kg}^{-1}\,\text{K}^{-1}$$

The relationships are then expressed in their simplest algebraic form as shown below:

$$Q = mc\Delta T$$

This is a good example of how careful experimentation provides useful data to find meaningful relationships (formulas). These relationships can then be used to predict what will happen under a different set of given conditions.

The specific heat capacity of water

Water has the highest specific heat capacity of most commonly occurring substances: 4180 J kg^{-1} K^{-1}. Water (a) heats up more slowly, (b) cools down more slowly and (c) stores more internal energy than the same mass of most other substances.

Many cooling and heating systems, from hot water bottles to water-cooled engines, utilise water's high specific heat capacity. Large bodies of water, such as oceans, seas and lakes, absorb large amounts of energy with only small temperature changes of the water.

heat sink
an object or material that moderates the temperature of its surroundings due to its large specific heat capacity

For the same amount of energy input, landmasses undergo much greater temperature changes. The temperatures inland are much hotter than on islands and in coastal regions. During the warmer months when the sea temperature is less than the average air temperature, the sea acts as a **heat sink**. During the colder months when sea temperature is warmer than the average air temperature, it releases the stored energy. This release of energy moderates the temperature of regions close to large bodies of water.

SECTION REVIEW 2.5

REMEMBERING

1. What does it mean when we say that the specific heat capacity of iron is $450\,\text{J kg}^{-1}\,\text{K}^{-1}$?
2. If 2000 J of heat is required to raise the temperature of an object by 1°C, by how much will the temperature of the same object increase if 4000 J of heat is added to it?
3. If 400 J of heat is required to raise the temperature of 1 kg of a substance by 1°C, how much heat will be required to raise the temperature of 500 g of the same substance by 1°C?

UNDERSTANDING

4. Use the specific heat formula $Q = mc\Delta T$ to derive the units of specific heat capacity.
5. Compare the specific heat capacities of ice, water and steam, and rank them in increasing order of the heat required to raise each of their temperature by 1°C.

ANALYSING

6. Discuss why the high specific heat capacity of water is important for its use in heating and cooling systems.

2.6 Solving problems: specific heat capacity

As a general rule, when solving problems for specific heat capacity, it is important to check the given units and if necessary convert them to the SI equivalent. It is also important to note that although the equation for solving specific heat capacity looks simple, it has four terms that require careful application.

The specific heat capacity, c, of the substance being investigated will generally be given in the wording of the problem or will be easily accessible in a table such as Table 2.5.1 (page 38). Be sure to use the correct physical state of the substance as the solid, liquid and gaseous phases of a substance will all have different specific heat capacities.

The specific heat capacity should always be used with units of $\text{J kg}^{-1}\,\text{K}^{-1}$, but occasionally will be reported in $\text{J kg}^{-1}\,°\text{C}^{-1}$, $\text{kJ kg}^{-1}\,\text{K}^{-1}$ or even $\text{kcal kg}^{-1}\,\text{K}^{-1}$. If you do see these units in a problem, be sure to convert them to the correct SI units.

In the first instance, since the temperature interval in the Celsius scale is the same as in the Kelvin scale, and it is the change in temperature that we are interested in, the units of $\text{J kg}^{-1}\,°\text{C}^{-1}$ and $\text{J kg}^{-1}\,\text{K}^{-1}$ are entirely equivalent. They can be used interchangeably.

In the second instance, since 1 kJ is equal to 1000 J, to convert $\text{kJ kg}^{-1}\,\text{K}^{-1}$ to the more standard form of $\text{J kg}^{-1}\,\text{K}^{-1}$, we need only to multiply by 1000.

In the final instance, 1 cal = 4.18 J, so 1 kcal = 4180 J. Therefore, to convert $\text{kcal kg}^{-1}\,\text{K}^{-1}$ to $\text{J kg}^{-1}\,\text{K}^{-1}$, we need to multiply by 4180.

In the specific heat equation, ΔT represents the change in temperature and can therefore also be written as $T_{\text{final}} - T_{\text{initial}}$. In the case where an object increases in temperature, T_{final} will be greater than T_{initial} and therefore ΔT will be a positive number. If this is placed in the equation for specific heat, Q will be also be calculated to be a positive number, indicating that heat has been added to the object.

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WORKED EXAMPLE 2.6.1

Convert 0.22 $kcal\,kg^{-1}\,K^{-1}$, the specific heat of aluminium, into $J\,kg^{-1}\,K^{-1}$.

ANSWER

4180 J = 1 kcal so multiplying by $\frac{4180\ J}{1\ kcal}$ is the same as multiplying by 1:

$$0.22\ \frac{kcal}{kg\ K} \times \frac{4180\ J}{1\ kcal}$$

Cancel the kcal in the numerator and denominator:

$$= 0.22\frac{\cancel{kcal}}{kg\ K} \times \frac{4180\ J}{\cancel{1\ kcal}}$$

Calculate the answer:

$$0.22\ kcal\,kg^{-1}\,K^{-1} = 919.6\ J\,kg^{-1}\,K^{-1}$$

Give the answer to the correct number of significant figures:

$$0.22\ kcal\,kg^{-1}\,K^{-1} = 920\ J\,kg^{-1}\,K^{-1}$$

The specific heat of aluminium is 920 $J\,kg^{-1}\,K^{-1}$.

WORKED EXAMPLE 2.6.2

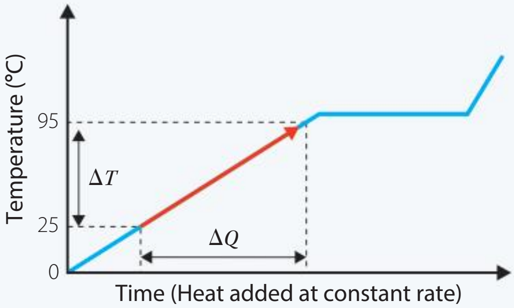
250 mL of pure water at 25°C is heated to 95°C.

a Sketch a graph representing the heating of the water from 0°C to 100°C. On the graph, show the section relevant to this question.

b How much energy is needed to achieve this temperature change?

ANSWERS

a As the temperature of a substance is directly proportional to the heat added, the graph will be linear.



b Use the correct equation:

$Q = mc\Delta T$

Substitute known values into the equation and find c for pure water in Table 2.5.1 (page 38):

$Q = 0.250\ kg \times 4180\ J\,kg^{-1}\,K^{-1} \times (95°C - 25°C)$

Calculate the correct answer: as Q is positive, heat is added, as it should be.

$Q = 7.3150 \times 10^4\ J$

Give the answer to the correct number of significant figures:

$Q = 7.3 \times 10^4\ J$

The energy needed to achieve this temperature change is 7.3×10^4 J.

calorimeter
a highly insulated container that prevents heat energy being lost to the environment, used to measure quantities of heat

In the case where the temperature of an object decreases, T_{final} will be less than $T_{initial}$ and therefore ΔT will be a negative number. This will result in Q being a negative number, indicating that heat has been lost by the object.

Of course, the specific heat formula can be algebraically rearranged to find any of the variables contained within it.

WORKED EXAMPLE 2.6.3

Calculate the mass of air in a sample if the addition of 48 000 J of heat to the sample results in an increase in temperature of 16°C.

ANSWER

Use the correct equation:

$$Q = mc\Delta T$$

Multiply both sides by $\frac{1}{c\Delta T}$ to get m by itself:

$$Q \times \frac{1}{c\Delta T} = mc\Delta T \times \frac{1}{c\Delta T}$$

Make m the subject:

$$m = \frac{Q}{c\Delta T}$$

Insert known values, retrieving c_{air} from Table 2.5.1 (page 38):

$$m = \frac{48\,000\ \text{J}}{1000\ \text{J kg}^{-1}\text{K}^{-1} \times 16°\text{C}}$$

Calculate the answer:

$$m = 3\ \text{kg}$$

Give the answer to the correct number of significant figures:

$$m = 3.0\ \text{kg}$$

The mass of air in the sample is 3.0 kg.

power
the rate at which work is done by a system, or the rate at which energy is being transferred

watt (W)
the unit of power; $1\ \text{W} = 1\ \text{J s}^{-1}$

Calorimeter

A common piece of experimental equipment used in the field of thermodynamics is the **calorimeter**. A calorimeter uses a highly insulating material to ensure that almost no heat is lost to the environment. In this way, any heat added to a liquid held within a calorimeter will flow into the calorimeter rather than be released into the environment.

Generally, heat is added to the sample by using a heating element of known **power**. Power is a measure of energy per time and is given the unit of **watt (W)**: 1 watt is equal to $1\ \text{J s}^{-1}$.

Power can also be calculated from the current travelling through and the voltage across the heating element : $P = I \times V$

Using these formulas, the amount of heat added to a substance can be found by multiplying the power by the time over which it is acting: $Q = P \times t$

KEY FORMULA

Power through a heating element

$P = I \times V$

Where:

P = power measured in watts ($1\ \text{W} = 1\ \text{J s}^{-1}$)

I = current measured in amperes (A)

V = voltage measured in volts (V)

WORKED EXAMPLE 2.6.4

2.5 A of current passes through a heating element when 2.0 V is applied over it. If this heating element adds heat to a 350 g sample of 5.0°C liquid water in a calorimeter for 30.0 minutes, what temperature will the water reach?

ANSWER

Apply the equation:

$$Q = mc\Delta T$$

Rearrange for the unknown:

$$T_f = \frac{Q}{mc} + T_i \qquad (1)$$

As $Q = P \times t$ and $P = I \times V \Rightarrow Q = IVt \qquad (2)$

Substitute equation (2) into equation (1):

$$T_f = \frac{IVt}{mc} + T_i$$

Substitute known values into the equation:

$$T_f = \frac{2.5\text{ A} \times 2\text{ V} \times 1800\text{ s}}{0.35\text{ kg} \times 4180\text{ J kg}^{-1}\text{ K}^{-1}} + 5°\text{C}$$

Calculate the answer:

$$T_f = 11.15°\text{C}$$

Give the answer to the correct number of significant figures:

$$T_f = 11°\text{C}$$

The water reached a temperature of 11°C.

SECTION REVIEW 2.6

REMEMBERING

1 Define 'calorimeter'.

2 Identify the SI units for each of these terms.

- **a** Heat added, Q
- **b** Mass of the sample, m
- **c** Specific heat of the sample, c
- **d** Change in temperature of the sample

UNDERSTANDING

3 Rearrange the specific heat equation to make the final temperature, T_f, the subject.

4 If the current passing through a heating element doubles while the voltage over it remains the same, what happens to the power?

APPLYING

5 Calculate the amount of heat that needs to be added to 300.0 g of antifreeze to raise its temperature by 15.0°C.

6 Calculate the final temperature of a 2.0 kg soil sample at 25°C, when 2500 J of heat is added to it.

7 A current of 5.0 A passes through a heating element when 1.5 V is applied over it. If this heating element adds heat to a 0.20 kg sample of lead at 25°C in a calorimeter for 30.0 minutes, what temperature will the lead reach?

2.7 Practical skills: analysing and reporting data

raw data
original data taken directly from a measurement system

derived data
data that are deduced from raw data by mathematical manipulation, such as graphs, algebraic equations and geometric constructions

During the experimental process, **raw data** are collected by investigating any changes that a dependent variable undergoes as a result of changes made to the independent variable. It is very seldom, however, that these measured raw data do not require mathematical analysis to calculate some **derived data** of interest. The analysis can take many forms and often progresses from tables of data, through graphs of relationships and mathematical equations before a conclusive relationship can be determined. Of great importance is the fact that any uncertainties in the data must also be analysed.

This section will outline the basic steps used when analysing raw data and introduces the scientific conventions and language used when writing an experimental report.

Organising experimental data

The first step in analysing any experimental data is to organise it. This will usually involve tabulating the data. Graphs are a very useful way of representing data so that trends and relationships can be identified. There are many different sorts of graphs that can be used to organise and display data. These are described below.

Usually some calculations will need to be made on the raw data to be able to answer the experimental aims or to test the hypotheses. Remember to keep units on all quantities, so that any derived values have the correct units. Uncertainties will also need to be calculated on any derived quantities.

Tabulating data

If there are more than a few data points, then it is a good idea to display them in a table. There may be several tables for different experiments. For example, imagine that the temperature of five different materials as a function of time after heating them has been measured. In this case, there may be five tables of raw data, each with measurements of temperature as a function of time for a different material. A table summarising the data in some way will be useful. For example, a table showing the time taken for each material to drop from 55°C to 45°C may be useful. Alternatively, a table showing the change in temperature over a given time period may be more useful. There cannot be too many tables or graphs in the logbook. When the report is written, a decision can be made as to which are the most useful for communicating your results. Tables are useful for recording raw and derived data and can be placed in an electronic spreadsheet, and graphs provide interpretation and analysis of that data.

Graphing data

The most reliable way to identify a pattern in data or a relationship between variables is to plot a graph. If an equation forms part of the hypothesis, then that equation can be used to generate a fit on a graph of your data, as described below. Do not substitute data into a hypothesised equation and try to show that it fits.

A graph should be large and clear. The axes should be labelled with the names of the variables and their units. Choose a scale so that the data take up most of the plot area. This will often mean that the origin is not shown in the graph. Usually there is no reason why it should be.

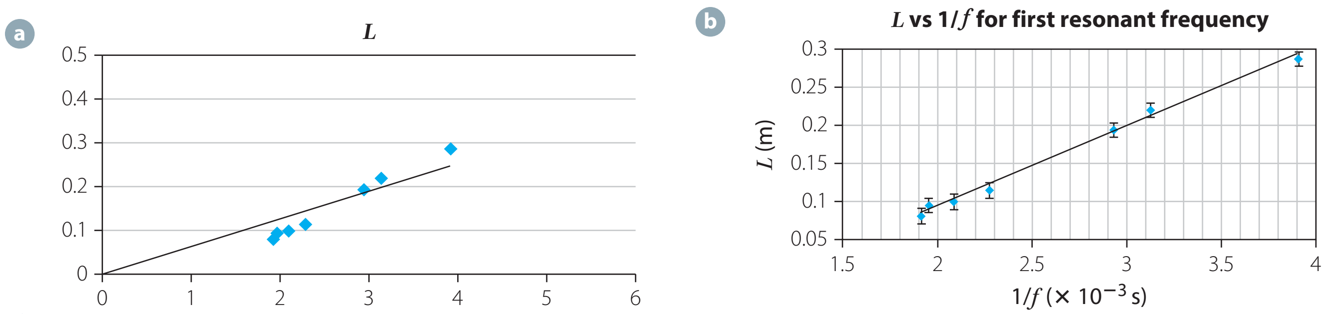


FIGURE 2.7.1 (**a**) A poor example of a graph. (**b**) A good example of a graph of the same data. How many problems can you identify on the graph in part a?

A scatter graph is used to show the relationship between variables, Usually the independent variable is plotted on the *x* axis and the dependent variable on the *y* axis, unless there is a good reason to do otherwise. Lines are often drawn on the scatter plots that indicate a correlation between the data points. This is called a regression line and is usually described in algebraic terms.

To determine a relationship there needs to be enough data points and the range of the data points should be as large as possible. A minimum of six data points is generally considered adequate if the relationship is expected to be linear. For non-linear relationships, try to collect more data in regions where rapid variation is expected. For example, if measuring an interference pattern (Figure 2.7.2), more than a hundred data points would be required to clearly see the sinusoidal pattern due to the two-slit interference.

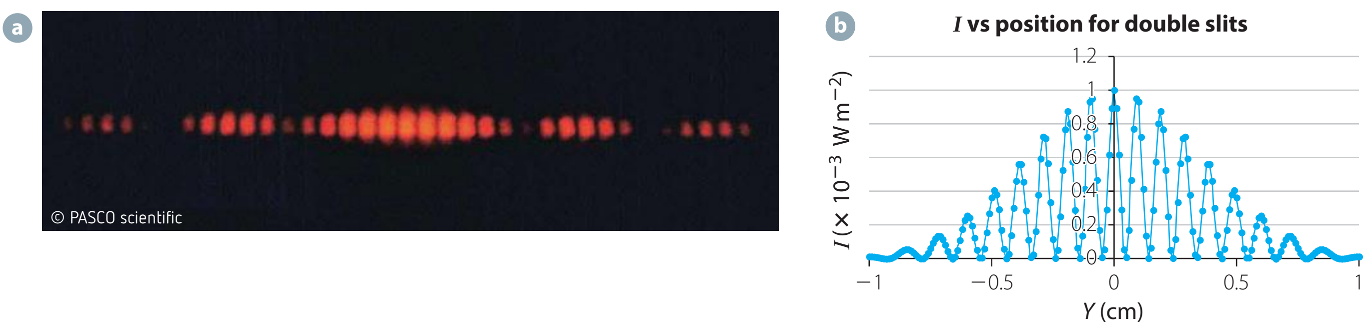


FIGURE 2.7.2 (**a**) Interference pattern from two slits; (**b**) Plot of intensity as a function of position for this experiment

A good graph to start with is simply a graph of the raw data. Whether the relationship is linear over the domain and range of the data will usually be obvious simply by looking at the graph. If it is linear, then fit a straight line using a graphing package. A linear regression tool can be used to check how good the straight-line fit is. This will give an R^2 number, which is a measure of how well the regression line fits with the data. The closer R^2 is to 1 (or −1), the better the fit. If R^2 is not *very* close to 1, then the relationship is not linear. Alternatively, the uncertainty in the gradient can be calculated by using lines of maximum and minimum gradient. If the uncertainty is large, then the relationship may not be linear.

If it is a linear relationship, then finding the equation for the line of best fit may be useful. *Never* force a line of best fit through the origin. Often the intercept gives you useful information. It may even indicate a systematic error, such as a failure to calibrate equipment correctly.

When plotting raw data, one or two points may be outliers. Outliers are points that do not fit the pattern of the rest of the data. These points may be mistakes; for example, they may have been incorrectly recorded or a mistake may have been made during measurement. Outliers may also indicate something important.

For example, if they occur at extreme values of the independent variable then it might be that the behaviour of the system is linear in a certain range or domain only. This is the case for materials under stress. A choice may be made to ignore outliers when fitting a line to data, but this should always be justified.

extrapolation extension beyond the measured range of data to read or construct a new data point that has not been measured

interpolation to read or construct a new data point that has not been measured but is within the range of measured data

To extend a line of best fit beyond the measured points is called **extrapolation**. Any data point that is read off a graph outside the range of the data points is extrapolated, and should be viewed with caution as it cannot be stated with certainty that the system continues to behave in the same way beyond the bounds of the data.

Reading points, other than data points, from a line of best fit within the region in which there is data is called **interpolation**. It is not possible to be certain that this is exactly what would be found if that point was actually measured; however, if the line of best fit genuinely represents the true trend of the behaviour of the system, then the interpolated points can be confidently used in an analysis.

Relationships between variables are often not linear. If raw data are plotted, for example the height of a rocket trajectory as a function of pressure, and it is a curve, then *do not draw a straight line through it*. In this case, a little more thought is required. If the hypothesis predicts the shape of the curve, then try fitting a theoretical curve to the data. If the curve fits well, then the hypothesis is supported.

linearise to make linear; to convert to a form that can be described by a straight line

If the hypothesis suggests that the data should produce a straight-line correlation, then **linearise** the data. Linear graphs have equations of the form $y = mx + c$. Here y is the variable plotted on the vertical axis, usually the dependent variable. The independent variable x is the variable plotted on the horizontal axis. The gradient is $m = \Delta y/\Delta x$. The constant c is the y intercept.

For example, if the hypothesis is that $h = \frac{1}{2}gt^2$, try plotting the data as a function of t^2. Here h is the initial height of a falling object, g is the acceleration due to gravity, and t is the time taken for it to fall:

$$h = \left(\frac{1}{2}g\right)t^2 + 0$$

$$\uparrow \quad \uparrow \quad \uparrow \quad \uparrow$$

$$y = m \; x + c$$

Hence a plot of h vs t^2 should be a straight line with gradient $\frac{1}{2}g$ and a y intercept of zero. If the plot of h vs t^2 is a straight line with gradient $\frac{1}{2}g$ with a y intercept of zero, then the hypothesis is supported.

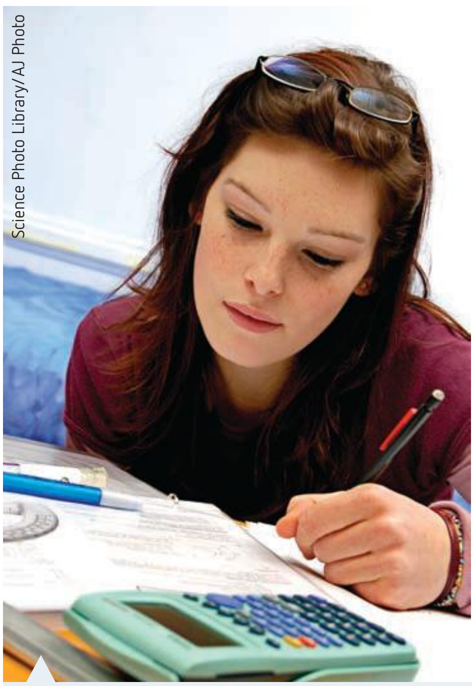

Science Photo Library/AJ Photo

FIGURE 2.7.3 You will usually need to analyse your raw data in some way.

Performing calculations on data

Some form of calculation will usually have to be performed on the data as part of the analysis. When the data were recorded, the units for all measurements were also noted. These may need to be converted to SI units (e.g. cm to m). Include the units with all numbers as calculations are made. In this way, it can be ensured that all derived data have the correct units. It also allows a check that any equations used are dimensionally correct.

It is good practice *in general*, not just in investigations, to include units at each step in all calculations.

Raw data and derived results should always be recorded with uncertainties.

Propagating uncertainty

Any uncertainty in the raw data must be considered when reporting derived data. In many instances data are given without uncertainty values. In these cases, the last decimal place represents the first uncertain figure. The number of significant figures in each value is the number of digits, taking into account the rules for significant figures.

Adding and subtracting raw data

When adding and subtracting numbers with uncertainties, it is useful to take advantage of place value. Perform the operation with the best estimate values. Add the uncertainties for each value to find the total uncertainty in the sum or difference. Claim the best estimate only as far as the sum of uncertainties will allow; that is, the place value of the first digit of the sum of the uncertainties. For example, consider the following sum:

$$(17.23 \pm 0.02) + (5.1 \pm 0.4)$$

Add the best estimates of the value: $17.23 + 5.1 = 22.33$
Add the uncertainties for each value: $0.02 + 0.4 = 0.42$

The answer could be given as 22.33 ± 0.42, but the result becomes uncertain at the first decimal place in the uncertainty, 4 in 0.42. Hence, the best estimate of the sum, with uncertainty, is 22.3 ± 0.4.

When there is no uncertainty given in a data point, the *last decimal* place in each number is regarded as the first uncertain figure. Then the result must have no more decimal places than the number with the least number of decimal places. The addition or subtraction is performed with the numbers as given, then rounded up from 5 or down from 4. For example:

$$\begin{array}{r} 32.2187 \\ +\,126.3 \\ +\quad 3.132 \\ \hline 161.6507 \end{array}$$

This is rounded up (0.65 to 0.7) to 161.7 because the number 126.3 is given to only one decimal place.

$$\begin{array}{r} 3052.3 \\ -\;235 \\ \hline 2817.3 \end{array}$$

This is rounded down (0.3 to 0) to 2817 because the number 235 is given to the nearest whole number.

Multiplying and dividing raw data

When multiplying, and dividing numbers with uncertainties, perform the operation using the best estimate values. Add the individual relative or percentage uncertainties to find the relative or percentage uncertainty in the product or quotient. To find a value for the uncertainty, the percentage or proportional uncertainty is used. For example, consider the following product:

$$(50.6 \pm 0.8) \times (123.63 \pm 0.91)$$

Multiply the best estimates: $50.6 \times 123.63 = 6255.678$
Find the percentage uncertainties for each number:

$$\frac{0.8}{50.6} \times 100\% = 1.581\% \text{ and } \frac{0.91}{123.63} \times 100\% = 0.736\%$$

Add the percentage uncertainties:

$$\begin{aligned} 1.58\% + 0.736\% &= 2.317\% \\ &= 2.3\% \text{ by convention} \end{aligned}$$

The product can be given as $6255.68 \pm 2.3\%$, but this hides a problem. The product has far more significant figures than the individual raw data numbers from which it was calculated. That is, the derived quantity is claimed to be more accurate than the raw data from which it was derived, which it cannot be.

Let us look at the actual value of the uncertainty:

$$2.3\% \text{ of } 6255.68 = 143.88$$

The result could now be reported, inaccurately, as (6255.68 ± 143.88). The result, 6255.68, is shown to be uncertain in the hundreds column. Using standard form to express the significant figures, the result should now be written, correctly, as:

$$(6.2 \pm 0.1) \times 10^3$$

As long as the raw data measure what is intended, this is an accurate and precise statement of the derived quantity. Notice, however, that the derived quantity has two significant figures. This is less than the number of significant figures in the number with the least significant figures, namely 50.6 (three significant figures). The number of significant figures in a derived quantity is always equal to or less than the number of significant figures in the least precise piece of raw data. In experiments, physicists try to ensure that uncertainties in the raw data do not accumulate to the point where derived quantities become meaningless. This takes high-level thinking, planning and effort.

When there is no uncertainty given in the data, calculations are performed using the unrounded data. The result is then rounded to a figure that has the same number of significant figures as the data with the *least number of significant figures*.

Two examples follow.

i 45.71 (4 significant figures)
$\times$ 34.1 (3 significant figures)
1558.711 (7 significant figures on calculator)

This is rounded to 1.56×10^3 (3 significant figures) because 34.1 has the least number of significant figures (i.e. 3).

ii $\frac{5465.48}{2.4}$ (a 6 significant figure number divided by a 2 significant figure number)

$= 2277.283333$ (10 significant figures on the calculator)

$= 2.3 \times 10^3$ (2 significant figures)

This is rounded to 2.3×10^3 because 2.4 has the least number of significant figures (i.e. 2).

Applying other functions on raw data

Sometimes, measurements are used in functions such as sin, cos and tan. An uncertainty value can be found numerically, rather than by applying the rules outlined above. Consider the way the function works before deciding how to proceed.

WORKED EXAMPLE 2.7.1

A student conducts an experiment to find the refractive index of an organic liquid. Angles of incidence, *i*, and angles of refraction, *R*, are measured several times and an average, with uncertainty, is found for each. The refractive index is then calculated from the equation:

$$n = \frac{\sin(i)}{\sin(R)}$$

Use the following data to calculate the refractive index, with uncertainty:
$i = (43.6 \pm 0.5)°$, $R = (32.1 \pm 0.5)°$

ANSWER

Calculate the refractive index from the best value estimate. Substitute the known values and calculate the answer.

$$n = \frac{\sin(43.6°)}{\sin(32.1°)} = 1.298$$

Decide what is the worst case possible. As the sine function is increasing in the range of possible values, substitute the known values and calculate the answer.

$$n = \frac{\sin(43.6 + 0.5°)}{\sin(32.1 - 0.5°)} = \frac{\sin(44.1°)}{\sin(31.6°)} = 1.328$$

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The difference between these two values is:

$$1.328 - 1.298 = 0.030$$

This shows the second decimal place is uncertain, so the answer must not go beyond the second decimal place.

Thus, after rounding, the refractive index, n, of the liquid is 1.30 ± 0.03.

Large data sets

For larger data sets requiring multiple manipulations, it is recommended that spreadsheets are used. That way it will be much easier to graph raw and derived data values for further analysis.

Report writing

A report is a formal and carefully structured account of scientific research and is based on data and an analysis of the logbook. The report is a summary containing a fraction of what appears in the logbook. It is written in the past tense as it is about what has been done.

A report consists of several distinct sections, each with a particular purpose.

- Abstract
- Introduction
- Method
- Results and analysis
- Discussion
- Conclusion
- Acknowledgements
- References
- Appendices

Abstract

The abstract is a very short summary of the entire report. It is the most important part, because it is the first part that people read. Typically, an abstract is between 50 and 200 words long. It appears at the start of the report, but is always the last part written. It usually has one sentence for each part of the report.

Introduction

The introduction tells the reader why the investigation was performed and states the research question or hypothesis. This is the place to explain why this research has been conducted.

The introduction also provides any background information needed to be able to understand the rest of the report. This is the place to summarise any existing theories, models, and any similar investigations. All of this should be correctly referenced.

Method

The method describes the scientific investigation and summarises what was measured and how it was measured. It also explains, briefly, why a particular method or technique was chosen. The method is written in dot points using past tense.

Include any diagrams, such as circuit diagrams, needed to make the method clear. The diagrams in the logbook will usually be rough sketches, but any diagrams in the report should be very neat and carefully labelled. Flow charts can be useful to describe any procedures in which a series of steps was followed. Each diagram should have a figure number and should be referred to in the text of the report. Position the diagram close to where it is referred to in the text.

Results and analysis

The results section is a *summary* of results. It is usually combined with the analysis section, although they may be kept separate.

Avoid including tables of raw data in a report unless they compare the results of a few different experiments. For example, a table showing the maximum height attained for a few different designs of water rocket would be included. However, a table of raw data showing the height attained for a water rocket for many different volumes of water would not be included. Wherever possible use a graph instead of a table.

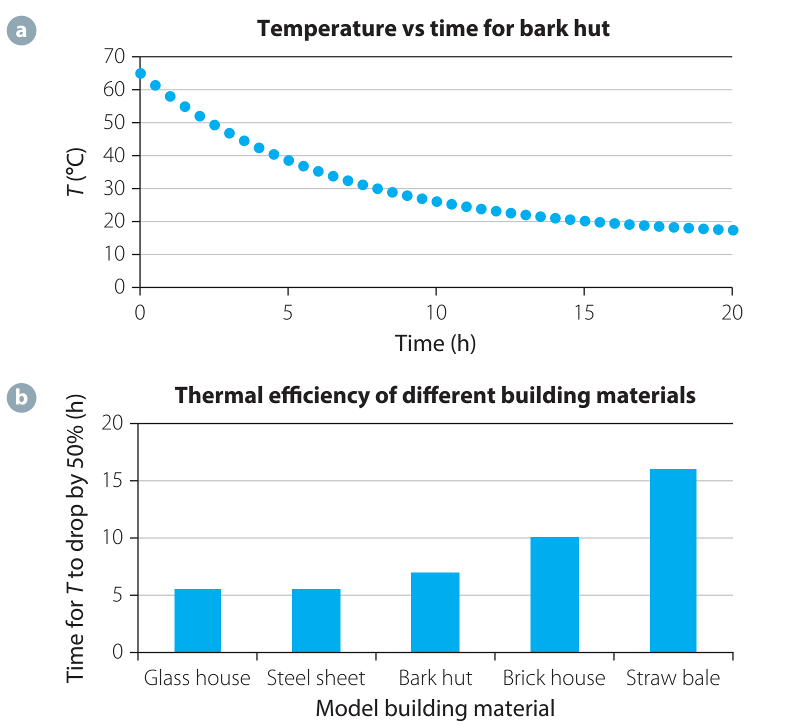
If a table has more than a few rows of data, it is better to include the raw data in the appendix and represent that data in some other way, usually as a graph.

To show a relationship between two variables use a scatter plot. Display the data as points with uncertainty bars and clearly label any lines fitted to the data. Always make sure to label the axes, including units, and choose an appropriate scale so that the data take up most of the plot area.

Column and bar charts are useful for comparing two data sets, such as average height attained for different types of water rocket. Do not use a column or bar chart to try to show a mathematical relationship between variables. In general, column or bar charts can be used to represent qualitative or discreet data; quantitative or continuous data is best represented by line graphs.

Figure 2.7.4 gives examples of the two types of graphs.

FIGURE 2.7.4
(**a**) A scatter plot demonstrating a mathematical relationship;
(**b**) A column graph comparing results from different experiments



Any data and derived results should be given in correct SI units with their uncertainties. If calculations were performed, then the equations used should be shown.

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Discussion

The discussion should summarise *what the results mean*. If the investigation began with a research question, give the answer to the question here. If the investigation began with a hypothesis, state whether the results support the hypothesis or not. If the hypothesis was not supported, it is important to explain why, even if it is because the model was not suitable for the situation being investigated.

Some reference to the quantitative size of the errors that are recorded and whether the experimental value found is appropriate given the error range should be made in the discussion.

If there are any implications of the work, such as how to build or do something in a better way, this should also form part of the discussion.

The discussion is also the place to briefly describe any difficulties encountered and make suggestions for improving the process.

Conclusion

The conclusion is a *very* brief summary of the results and their implications. State what was found and what it means. A conclusion should only be a few sentences long.

Acknowledgements

Thank anyone who helped in the investigation. This includes people who supplied equipment or funding, as well as people who gave good ideas or helped with the analysis. In science, as in other aspects of life, it is polite to say thank you; however, this is not a necessary section of a report.

References

A reference list details the source for each piece of information used, and is linked to that information in the report.

The reference list details the sources of all information that was actually used to write the report. Wherever a piece of information or quotation is used in the report, it must be referenced *at that point*. This is typically done either by placing a number in brackets at the point [2], or the author and year of publication (Smith, 2014). The reference list is then either provided in a footnote at the bottom of the page, or as a single complete list at the end of the report. Referencing must be done in a consistent style. Check with the teacher what style is preferred. There are several good online guides to referencing.

2.7.1 Referencing guide

A reference list is *not* the same as a bibliography. A bibliography is a list of sources that are useful to understanding the research. They may or may not have been used by the report authors. There should be a bibliography in your logbook from the planning stage of the investigation. The references will be a subset of these sources.

Appendices

Appendices may be used to provide additional information such as raw data that are not necessary to understanding the report but which might be of interest to some readers. A teacher might require raw data in an appendix. Reports do not always have appendices.

2.8 Interpreting specific heat data

In Mandatory practical activity 2.8.1, you will be asked to calculate the specific heat capacity of water by adding heat to it by means of a submersed electric resistor.

During the experiment, you will be able to collect data relating to the amount of heat added (the independent variable) and the resulting temperature change of the water (the dependent variable).

This section will assist you to interpret both the tabulated and graphical data in order to be able to calculate the specific heat capacity of the water and its resulting percentage error.

thermistor temperature-dependent resistor; used to detect changes in temperature

Table 2.8.1 shows the raw data of an experiment in which a **thermistor** with a power rating of 5.0 W was submerged in 500.0 g of water. Temperature readings were taken every 30.0 s for 10.0 minutes.

TABLE 2.8.1 Experimental data set of time vs temperature of a water sample heated by a 5.0 W thermistor

TIME (S)	TEMPERATURE (°C)	TIME (S)	TEMPERATURE (°C)
0.0	24.50	330.0	25.19
30.0	24.56	360.0	25.26
60.0	24.63	390.0	25.32
90.0	24.69	420.0	25.38
120.0	24.75	450.0	25.45
150.0	24.82	480.0	25.51
180.0	24.88	510.0	25.57
210.0	24.94	540.0	25.64
240.0	25.01	570.0	25.70
270.0	25.07	600.0	25.76
300.0	25.13		

The first issue that can be seen is that the table does not contain any reference to heat added to the water. The clue to solving this is the inclusion of the information that the thermistor had a power rating of 5.0 W. Power is a measure of energy per time, and since it can be assumed that all of this energy is being transformed to heat, the thermistor is providing 5.0 J of heat to the water every second.

Using the information in the time column, we could add another 'heat' column in our table using the formula: $Q = P \times t = 5.0\,\mathrm{J\,s^{-1}} \times t(\mathrm{s})$

Even though you may be able to see that the amount of heat added is increasing in regular increments, as would be expected for a constant heat source, it is difficult to make out any relationship between heat added and the temperature of the water source simply by looking at the table.

The next step would be to create a scatter plot of the data. This could be done by hand, by using a graphics calculator or by using a spreadsheet software.

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TABLE 2.8.2 Experimental data set of heat added vs temperature of a water sample

TIME (S)	HEAT ADDED (J)	TEMPERATURE (°C)
0.0	0.0	24.50
30.0	150.0	24.56
60.0	300.0	24.63
90.0	450.0	24.69
120.0	600.0	24.75
150.0	750.0	24.82
180.0	900.0	24.88
210.0	1050.0	24.94
240.0	1200.0	25.01
270.0	1350.0	25.07
300.0	1500.0	25.13
330.0	1650.0	25.19
360.0	1800.0	25.26
390.0	1950.0	25.32
420.0	2100.0	25.38
450.0	2250.0	25.45
480.0	2400.0	25.51
510.0	2550.0	25.57
540.0	2700.0	25.64
570.0	2850.0	25.70
600.0	3000.0	25.76

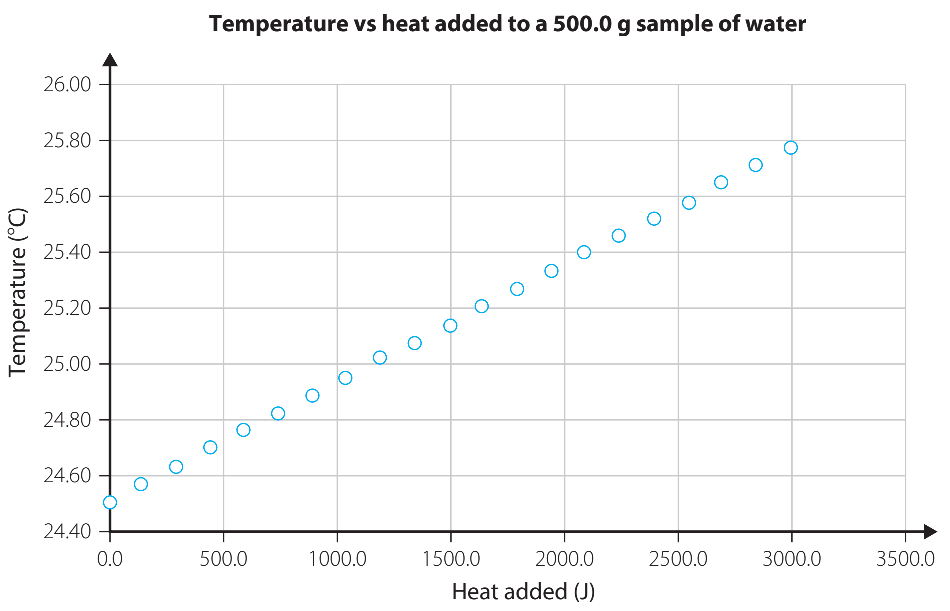


FIGURE 2.8.1 Graphical representation of temperature vs heat added for data from Table 2.8.2

There are quite a few features that can be seen on this graph. First, note the inclusion of a graph title and axes titles including the units of each variable. Note also that the dependent variable (heat added) is on the x axis and the dependent variable is on the y axis. Finally, it is evident from the graph that there is a linear relationship between the two variables and we could go on and calculate the equation of the line of best fit if we chose to. Many spreadsheet programs will draw graphs of highlighted columns, draw in a regression line and provide a mathematical equation for that line. You should be familiar with how such programs work.

From the specific heat formula, we know the relationship between heat added and temperature is:

$$Q = mc\Delta T$$

Since temperature is on the y axis and heat added is on the x axis, we could rearrange this equation to the more appropriate form:

$$\Delta T = \frac{Q}{mc}$$

Since $\Delta T = T - T_o$ (where T_o) is the initial temperature, this equation could be written as:

$$T - T_o = \frac{Q}{mc}$$

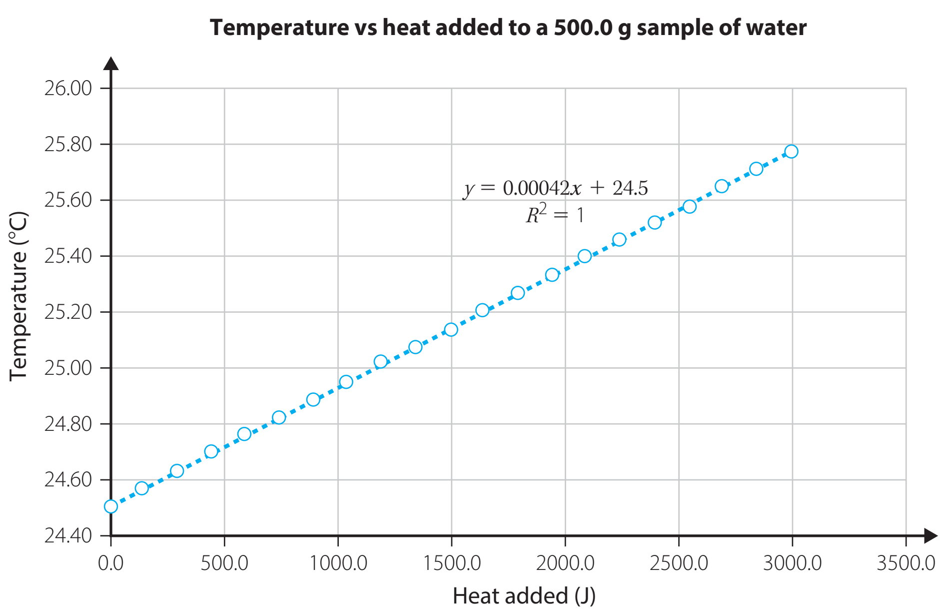
Finally, we could rearrange this into the form:

$$T = \frac{Q}{mc} + T_o$$

which is in the form of the linear equation $y = mx + c$, with a y value of temperature, a gradient of $\frac{1}{\text{mass} \times \text{specific heat}}$, an x value of heat added and a y intercept of initial temperature.

We could now find the equation of a straight line fit, knowing that this will yield a valid relationship.

FIGURE 2.8.2 Line of best fit for temperature vs heat added



The equation of the line has been included, but we could just as easily have derived the equation by finding the y intercept of 24.5°C and by calculating the gradient by the rise over run as 0.00042 J °C^{-1}.

The R^2 value of 1 indicates that the line is a perfect fit; it is unlikely that experimental data would achieve such a value.

The y intercept of 24.5°C agrees with the data set in that the water sample did indeed have an initial temperature of 24.5°C.

Finally, the gradient of the line has a value of $0.00042\,\text{JK}^{-1}$, which we can equate to $\frac{1}{\text{mass} \times \text{specific heat}}$, and since we know the mass of the sample, we can solve for the specific heat capacity.

$$0.00042\ \text{JK}^{-1} = \frac{1}{m \times c}$$

$$c = \frac{1}{m \times (0.00042\ \text{JK}^{-1})}$$

$$c = \frac{1}{(0.5\ \text{kg})(0.00042\ \text{JK}^{-1})}$$

$$c = 4761.9$$

or correct to two significant figures:

$$c = 4800\ \ \text{J kg}^{-1}\text{K}^{-1}$$

We have calculated the specific heat capacity of water from experimental data and it is time to evaluate our result. To do this, given that we have a commonly accepted value for the specific heat of water ($4180\,\text{J kg}^{-1}\text{K}^{-1}$) it makes most sense to calculate the percentage error.

$$\%\ \text{error} = \left|\frac{\text{measured value} - \text{accepted value}}{\text{accepted value}}\right| \times 100\%$$

$$\%\ \text{error} = \left|\frac{4800 - 4180}{4180}\right| \times 100\%$$

$$\%\ \text{error} = 14.8\%$$

MANDATORY PRACTICAL ACTIVITY 2.9.1

Specific heat capacity of water

In this experiment, you will be finding an experimental value for the specific heat capacity of water, but you will also use it as practice in writing a report that uses the correct scientific conventions and language as outlined in the previous section.

You should begin by writing an introduction, based on the content of the previous two sections. Remember to use correct referencing protocols.

AIM

To find the specific heat capacity of water

MATERIALS

- calorimeter
- immersion heater
- thermometer or calibrated temperature probe
- electronic scales
- sample of water

»

- galvanometer
- ammeter
- power supply
- 20 Ω 15-watt rheostat
- stopwatch

PROCEDURE

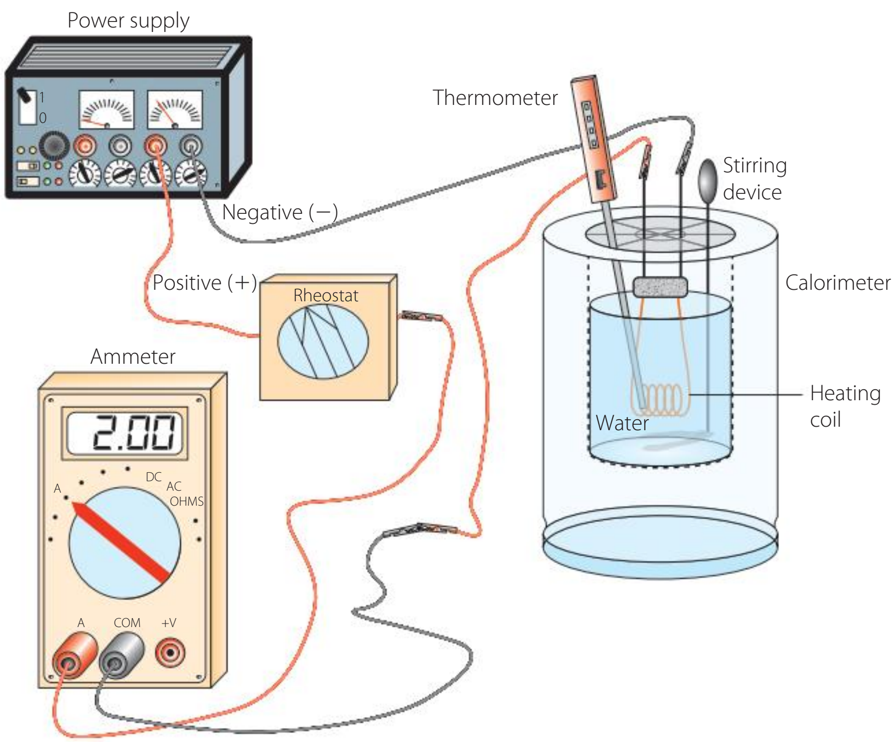


FIGURE 2.8.3 Experimental set-up for determination of the specific heat of water.

1. Measure and record the mass of the calorimeter.
2. Add approximately 150 mL of cold water to the calorimeter, and measure and record the mass of calorimeter and water.
3. Suspend the thermometer or temperature probe in the cold water.
4. Connect the power supply (set to approximately 5 V output), rheostat, galvanometer (or voltmeter), ammeter and immersion heater as shown in Figure 2.8.3
5. Turn on the power supply and adjust the rheostat so that the ammeter reads approximately 2 A.
6. With the voltage properly adjusted, record the voltage and current readings and then turn off the power supply.
7. Measure and record the initial temperature of the water.
8. Switch the power supply back on and start the stopwatch.
9. Stir regularly and record the temperature of the water at 20 s intervals.
10. After 15 minutes, turn off the power supply and record the final temperature of the water.

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» Add any other risks that you can think of and ways to manage them.

RISK ASSESSMENT

WHAT ARE THE RISKS IN DOING THIS EXPERIMENT?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
Heating equipment can cause burns.	Avoid touching the equipment. Wait for the equipment to cool before you put it away.
Electrical equipment may cause shocks or electrocution.	Double-check that all electrical equipment is in good working order. Avoid touching the electrical equipment while it is being used.
Hot water can scald.	Wear safety glasses. Avoid spilling or splashing boiling water.

RESULTS

Record results in tables similar to the tables below. Include an estimate of the uncertainty in each measurement (section 2.3, page 26). Heat added can be calculated as shown in section 2.6, page 40.

Table of results part 1

DATA	TRIAL 1	TRIAL 2
Mass of calorimeter (g)		
Mass of cold water and calorimeter (g)		
Mass of cold water (g)		
Voltage (V)		
Current (A)		
Power output (W) ($P = V \times I$)		

Table of results part 2

TIME (S)	HEAT ADDED (J)	TEMPERATURE (°C)	
		TRIAL 1	TRIAL 2
0.0			
30.0			
60.0			
90.0			
120.0			
150.0			
180.0			
210.0			
240.0			
270.0			

TIME (S)	HEAT ADDED (J)	TEMPERATURE (°C)	
		TRIAL 1	TRIAL 2
300.0			
330.0			
360.0			
390.0			
420.0			
450.0			
480.0			
510.0			
540.0			
570.0			
600.0			

ANALYSIS OF RESULTS

1 Use the data to graph temperature vs heat added for both trials.
2 Draw a line of best fit for the graph and calculate the equation of the line.
3 Use the equation of the line of best fit to find the specific heat capacity of water for each trial.
4 Use the data to determine the measurement value and the absolute uncertainty in the measurement value.
5 Look up the accepted value of the specific heat capacity of water, including the uncertainty associated with this value. Decide whether the range of your measurement value overlaps the range of the accepted value.
6 Calculate the percentage error in your data.

DISCUSSION

1 How well does your calculated specific heat capacity of water compare with the accepted true value?
2 Using concepts such as systematic and random error, explain any disparity between your calculated value and the accepted value of the specific heat of water.
3 What elements of the experiment could be improved in order to derive a more precise measurement of the specific heat of water?

CONCLUSION

Write a conclusion to answer your aim.

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MANDATORY PRACTICAL ACTIVITY 2.9.2

Specific heat capacity of metals

Experiments have demonstrated that a small metal block will take about 3–5 minutes to come to thermal equilibrium with boiling water. Once it has reached this temperature, it can be placed in a known mass of water (specific heat capacity = 4180 J kg^{-1} K^{-1}) at a different temperature. Left for long enough in a calorimeter, the two will reach the same temperature and it can be assumed that the water absorbs all of the heat released by the metal block. From this and the mass of the metal block, the specific heat capacity of the metal can be calculated.

AIM

To find the specific heat capacity of one or more metals

MATERIALS

- calorimeter
- thermometer or calibrated temperature probe
- heating equipment
- glass stirring rod
- electronic scales
- different metal cubes with dimensions about 2 cm × 2 cm × 2 cm
- strong cotton thread
- paper towel

PROCEDURE

1. Set up the equipment as shown in Figure 2.8.4.
2. Heat the water until it is boiling.
3. Determine the mass of the metal cube and securely tie the cotton thread around it.
4. Gently lower the metal cube into the boiling water and leave until it is at 100°C (3–5 minutes).
5. Measure and record the mass of the calorimeter.
6. Add approximately 150 mL of cold water to the calorimeter and measure and record the mass of calorimeter and water.
7. Suspend the thermometer or temperature probe in the cold water.
8. Gently stir the water with the stirring rod and wait for the temperature of the water and the thermometer or temperature probe to come to equilibrium. Record this temperature.
9. Carefully lift the hot metal cube out of the boiling water, quickly dry it, then lower it gently into the calorimeter water. Stir the water gently and frequently.
10. Record the temperature of the mixture of the metal block and the water when it reaches its maximum.
11. Repeat the experiment with a second trial.
12. If your teacher directs you to, repeat the experiment with a different metal.

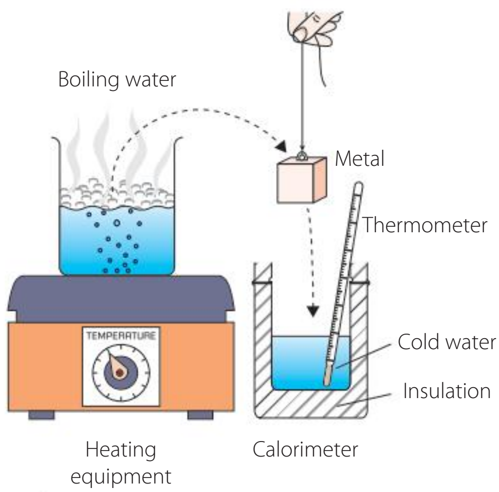

FIGURE 2.8.4 Experimental set-up for the transfer of the hot metal to the cold water

» Add any other risks that you can think of and ways to manage them.

RISK ASSESSMENT

WHAT ARE THE RISKS IN DOING THIS EXPERIMENT?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
Heating equipment can cause burns.	Avoid touching the equipment. Wait for the equipment to cool before you put it away.
It is possible to lose control of the hot block while transferring it from beaker to calorimeter or to burn yourself while doing so.	Double-check that the cotton thread is secured. Avoid touching the metal while transferring the block.
Boiling water can scald.	Wear safety glasses. Lower the block gently into the water. Avoid spilling or splashing boiling water.

RESULTS

Record results in a table similar to the table below. Include an estimate of the uncertainty in each measurement (see section 2.3).

DATA	TRIAL 1	TRIAL 2
Mass of metal block (g)		
Mass of calorimeter (g)		
Mass of cold water and calorimeter (g)		
Mass of cold water (g)		
Initial temperature of cold water and calorimeter (°C)		
Initial temperature of metal cube (°C)		
Final temperature of water and metal cube (°C)		

ANALYSIS OF RESULTS

1 Use the data to find the specific heat capacity of the metal for both trials.

2 Use the data to determine the measurement value and the absolute uncertainty in the measurement value.

3 Look up the accepted value of the specific heat capacity of the metal, including the uncertainty associated with this value. Decide whether the range of your measurement value overlaps the range of the accepted value.

DISCUSSION

1 Why were you instructed to dry the metal cube before placing it in the cold water?

2 Why is it desirable to start with the water temperature below room temperature and have a final temperature above room temperature?

3 Why were you asked to do two trials? Does this improve accuracy or precision?

4 Did your best estimate of the specific heat capacity of the metal differ from the accepted value? Explain.

5 Is it meaningful to calculate the percentage error in this experiment? Explain.

CONCLUSION

Write a conclusion to answer your aim.

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CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 Define the following terms.
 a Thermometer
 b Absolute zero
 c Diffusion
 d Specific heat capacity
 e Heat sink

2 Name some important temperatures that help to define:
 a the centigrade temperature scale.
 b the Kelvin temperature scale.

3 Use the kinetic particle model of matter to explain how the temperature of a substance is increased.

4 Explain what factors may affect the size of the temperature change an object experiences when a given amount of heat is added.

CATEGORY QUESTIONS

5 What is required to define a useful numerical temperature scale?

6 Give three examples of some properties that can be used to measure the temperature of an object.

7 Does a substance with a higher specific heat capacity require more or less energy to raise the temperature than an equal mass of a substance with a lower specific heat capacity?

8 Explain the properties of a substance that may impact upon its specific heat capacity.

ELABORATION QUESTIONS

9 Explain why the centigrade scale is in common usage even though scientists find the Kelvin scale more useful.

10 Suggest what the effects would be if liquid water had a lower specific heat capacity.

EVIDENCE QUESTIONS

11 Suggest a line of reasoning that would support the universal adaptation of the Kelvin temperature scale. How might this affect people who commonly use the Fahrenheit scale?

12 Water is commonly used as a heat sink for absorbing unwanted heat from power stations. Research other potential substances that could be used for this purpose and give reasons why they would be well suited or not for this purpose.

END-OF-CHAPTER EXAM

End-of-chapter test

1 Which of the following is a quantitative description?

A The block of iron is at a temperature that feels hot to the touch.

B The block of iron is at a temperature greater than that of the block of steel.

C The block of iron is at a temperature of 33.5°C.

D The block of iron is at a temperature equal to the temperature of the room.

2 A change in temperature of a substance cannot be due to:

A a change in the internal energy of the substance.

B a change in the average kinetic energy of the particles in the substance.

C a transfer of heat in or out of the substance.

D a change in the amount of potential energy stored in the particles of the substance.

3 If the temperature of a car's engine is 320°C on the Celsius scale, what would its temperature be on the Kelvin scale?

A 593 K

B 47 K

C 320 K

D 0 K

4 Which of the following is the SI unit for specific heat capacity?

A $J\,kg^{-1}$

B $cal\,kg^{-1}\,K$

C $cal\,kg^{-1}\,°C^{-1}$

D $J\,kg^{-1}\,K^{-1}$

5 To which of the following is the heat required to change the temperature of an object not proportional?

A The mass of the object

B The surface area of the object

C Specific heat capacity of the object

D The temperature change of the object

6 Which of the following substances would undergo the greatest increase in temperature for a given input of heat?

A 1 kg of water

B 1 kg of steam

C 1 kg of ice

D 1 kg of soil

7 Is the difference between 0°C and 1°C greater than, equal to or less than the difference between 273 K and 274 K?

8 What property of electricity does a thermostat use to measure temperature?

9 What is the term used for spontaneous movement of heat through a substance?

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10 Define 'heat sink'.

11 Explain the use of a calorimeter.

12 Explain the second law of thermodynamics as it relates to heat transfer.

13 Calculate the heat released when 450 g of molten glass (c_{glass} = 670 J kg^{-1} K^{-1}) at 465°C is cooled to room temperature (25°C). Note: molten glass and cooled glass are both considered liquids.

14 If 49 000 J of heat is added to 250 g of cooking oil initially at 25°C, calculate its final temperature.

15 What is the specific heat of a 1.8 kg sample of marble if 51 084 J of added heat results in an increase of temperature of 33°C?

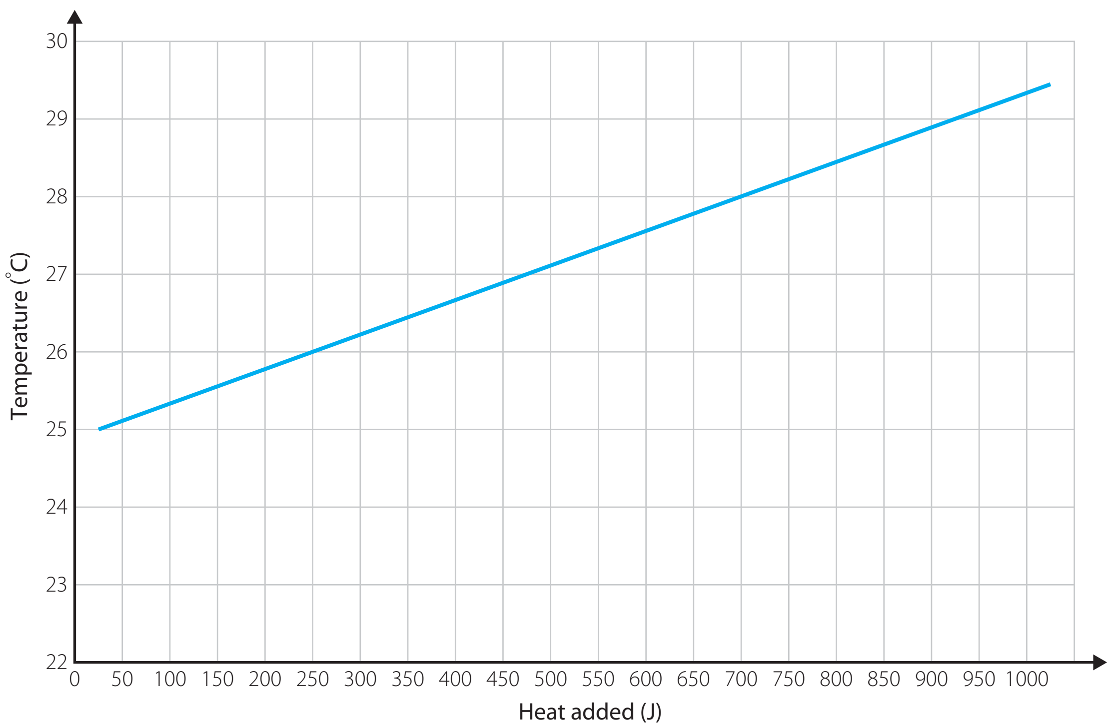
16 Use the kinetic particle model to explain what happens to the particles of a substance when heat is added to it.

17 The specific heat of a watermelon is very large, almost as large as that of water. Explain why this is.

18 Why do oceans have a moderating effect on the temperature of the land near them?

19 A current of 3.0 A passes through a heating element when 10.0 V is applied over it. If this heating element adds heat to a 1.0 kg sample of water at 25°C for 10.0 minutes, what is the final temperature of the water?

20 Use the graph below of the temperature change associated with the addition of heat to 0.5 kg of an unknown substance to calculate the specific heat capacity of the substance. Compare your result with the values in Table 2.5.1 (page 38) to suggest what the substance is composed of.



21 A 5.0 W immersion heater was placed in 250 g of a liquid sample and the results were recorded in the table below. Use these results to calculate the specific heat capacity of the substance, with the help of a graph.

Time (s)	Temperature (°C)
0.0	12.0
10.0	12.6
20.0	13.2
30.0	13.7
40.0	14.3
50.0	14.9
60.0	15.5
70.0	16.1
80.0	16.7
90.0	17.2
100.0	17.8
110.0	18.4
120.0	19.0
130.0	19.6
140.0	20.1
150.0	20.7
160.0	21.3
170.0	21.9
180.0	22.5
190.0	23.0
200.0	23.6

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3 PHASE CHANGES AND LATENT HEAT

Introduction

In Chapter 2, the way the temperature of objects changed when heat was added was discussed in terms of the specific heat capacity of the object. It is important to note that this concept only applied to objects that did not change their physical state between solid, liquid or gas.

In everyday experience, however, phase changes occur regularly, such as when ice melts in a glass of water, wet clothes are put on a line to dry or condensation forms on the inside of a windscreen.

In this chapter, you will discover what happens to the temperature of a substance as heat is added to it at a transition temperature at which it changes its physical state. This will be done by thoroughly investigating how particles interact when heat is added.

Stimulus questions

How does an object react when heat is added at its change of state temperature?

Why do you feel colder when you are wearing wet clothes?

Shutterstock.com/Bachkova Natalia

3.1 The process of state change

phase change
a change in physical state (e.g. solid to liquid)

When water in the solid phase (ice) is heated, its temperature will increase linearly with the amount of heat added. When it reaches 0°C, it will undergo a **phase change** and it will melt to form liquid water. If the heating continues, this liquid will once again increase in temperature until it reaches 100°C, at which it will undergo another phase change and boil into a gas (steam).

Melting and boiling points

melting point
the temperature at which a substance undergoes a phase change from solid to liquid (melts)

boiling point
the temperature at which a substance undergoes a phase change from liquid to gas (vaporises)

melting
the phase change from solid to liquid

vaporisation
the phase change from liquid to gas

condensation
the phase change from gas to liquid

solidification
the phase change from liquid to solid

sublimation
the phase change from solid to gas without becoming a liquid

deposition
the phase change from gas to solid without becoming a liquid

3.1.1 Matter changing phase

evaporation
the process in which some of the particles with high kinetic energy escape the surface of a liquid at a temperature below its boiling point

A pure solid starts to change state to a liquid at its **melting point**. A pure liquid starts to change state to a gas at its **boiling point**. Both processes, **melting** and **vaporisation** respectively, require energy input. Energy removal causes gases to undergo **condensation** and liquids to undergo **solidification**.

Some substances can change state (phase) directly from a solid to a gas (**sublimation**) or from a gas to a solid (**deposition**) without going through the liquid state. Solid carbon dioxide (dry ice) does this at −78.5°C. It is primarily used when a cooling process that does not leave a liquid residue is required.

These phase changes are shown in Figure 3.1.1 below.

Evaporation and vaporisation are often confused. At temperatures below the boiling point, evaporation from a liquid occurs at the surface. Some particles with high kinetic energy escape, as shown in Figure 3.1.2. When these high kinetic energy particles leave the liquid, the average kinetic energy of the liquid is reduced and the temperature therefore decreases. Vaporisation, however, occurs when the entire liquid changes to gas. No temperature change occurs during vaporisation. Vaporisation can be distinguished from evaporation by the fact that bubbles form below the surface.

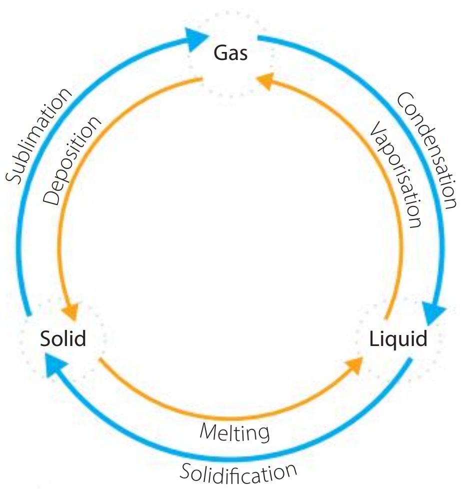

FIGURE 3.1.1 State change cycles. These cycles name each of the phase changes between one physical state and another.

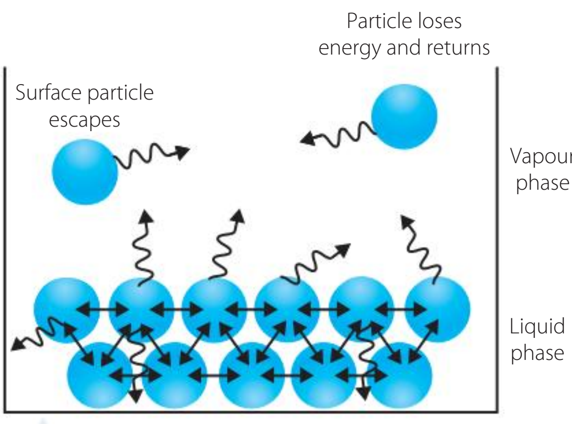

FIGURE 3.1.2 Evaporation occurs at the surface when water molecules that are less tightly bound and have relatively higher kinetic energy than those in the body of the water escape.

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Phase changes on a particle level

Particle interactions during phase changes can be illustrated by investigating what happens to a 1.0 kg block of ice as it is steadily heated at a constant rate from −50°C to steam at 100°C at stable pressure of 1 **atmosphere**.

Figure 3.1.3 shows the **heating curve** of water, which is a graph of temperature versus time or heat added. As can be seen, the temperature of ice rises at a steady rate of about 0.5°C for every kJ of heat that is added (section A). During this time, the random motion of the ice molecules increases as they gain more kinetic energy from the heat added.

atmosphere
unit of pressure; 1 atmosphere is the standard pressure found at the surface of the Earth

heating curve
a plot of temperature versus time or heat added

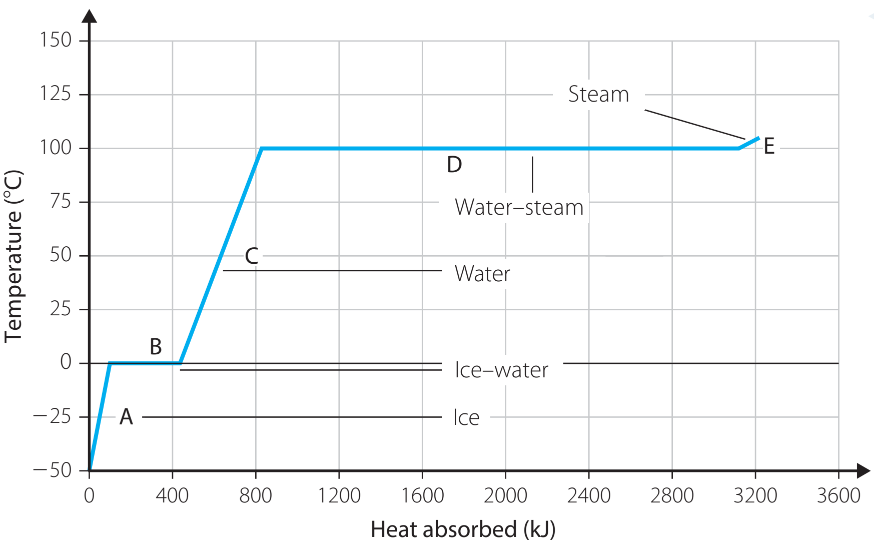


FIGURE 3.1.3 The heating curve of 1.0 kg of pure water. This graph indicates how the temperature of the water changes before, during and after each phase change when heat is steadily being added.

Eventually, some of the molecules gain enough energy to break loose from the bonds that are holding them bound in ice crystals. This is indicated by the plateau in the heating curve which occurs at 0°C (section B). At this temperature, which is called the melting point, the heat flowing into the ice does not result in an increase in temperature, but rather is used to disrupt the ice structure of individual molecules. These molecules collide with other molecules and transfer energy to them, in turn allowing them to break free from the ice-forming bonds. Although there is an increase in the internal energy of the sample, this process does not result in an increase in the average kinetic energy of the molecules (otherwise there would be an increase in temperature) but rather, results in an increase in the potential energy of the molecules.

The melting process continues at a constant temperature until all the molecules break free from the bonds and the phase change is complete. As can be seen from the heating curve, about 330 kJ of energy is required to turn 1 kg of ice at 0°C to water at 0°C.

As shown in Figure 3.1.3 (section C), when the sample is in the liquid phase, the temperature of the water increases at a steady rate of about 0.25°C for every 1 kJ of energy added, until it reaches its boiling point at 100°C. At this point, the temperature of the sample once again remains constant, as all the heat added is used to increase the potential energy of the molecules by making them energetic enough to break free from the bonds holding them together as liquid water (section D). In this way, the internal energy of the sample once again increases while the average kinetic energy of its particles (and therefore its temperature) does not.

The whole process of turning 1.0 kg of water at 100°C to steam at 100°C requires about 2260 kJ of energy. Once in the steam phase, the temperature of the 1.0 kg sample increases linearly with heat added at a rate of about 0.5°C per kJ of heat added (section E).

Both of these phase changes are reversible. For example, steam loses energy to its surroundings, cooling until it reaches its boiling point, remaining at a constant temperature while the water molecules get closer together. Energy is being released to the surroundings during the condensation process.

FIGURE 3.1.4 Distinctive anvil-shaped clouds are often seen at the tops of thunder clouds.

This energy comes from a reduction of the internal energy of the molecules as they draw closer together to form liquid water. This is why steam at 100°C will cause much more severe burns than the same mass of water at 100°C.

Condensation and heat exchange occurs in cloud formation. A pocket of moist air surrounded by dry air rises because it is less dense. It ascends into a cooler region, causing the water vapour to condense as clouds. The latent heat of vaporisation is released to the surrounding air, which becomes warmer. Warm air, being less dense than cooler air, continues to rise. Eventually, the moist air hits the 'roof' of the weather zone, the troposphere. Cloud formation then continues horizontally rather than vertically. Distinctive anvil-shaped clouds (Figure 3.1.4) form at the tops of thunder clouds, especially in the tropics.

SECTION REVIEW 3.1

REMEMBERING

1 Distinguish between vaporisation and evaporation.

2 Order the following processes for the heating of 1 kg of lead.

A Lead vaporises at 2296°C.

B Solid lead increases in temperature at a rate of 7.7°C per kJ of heat added.

C Liquid lead increases in temperature at a rate of 7.1°C per kJ of heat added.

D Lead melts at 873°C.

UNDERSTANDING

3 Discuss why the temperature of a liquid at its boiling point remains constant when it is changing state.

4 The line on a heating curve for a pure substance that is being heated between state changes has a constant linear slope. What does this imply about the heat supply?

5 The lines on a heating curve for a pure substance that is receiving a constant heat energy input during state changes are parallel to the horizontal axis. What does this imply?

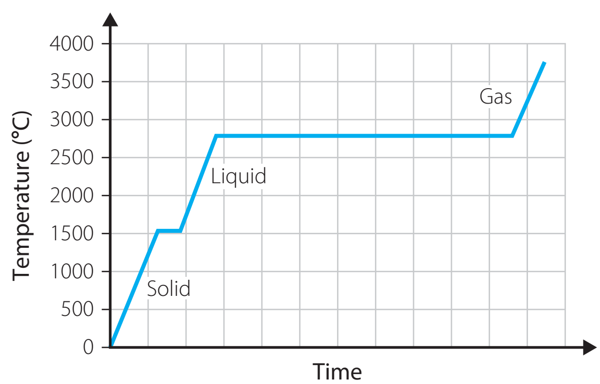
ANALYSING

6 Different substances have different melting points and boiling points, but the shapes of their heating curves are very similar. Solid iron is heated constantly from its solid state to its gaseous state in a furnace. The heating curve for the duration of this process is shown in Figure 3.1.5. Use the curve to answer the following questions.

a What is the melting point of iron?

b What is the boiling point of iron?

FIGURE 3.1.5 Heating curve for iron



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3.2 Defining specific latent heat

During a change of state, energy is added or removed. The energy added or removed during a state change is called the latent heat.

latent heat
the heat required to change the state of a substance at its boiling point or melting point without a change in temperature; unit: $J\,kg^{-1}$

The specific latent heat of fusion

The specific latent heat of fusion of a substance is the energy required to change the state of 1 kg of the substance from its solid state to its liquid state without any change in temperature. It is also the energy that is released when 1 kg of the same substance solidifies from liquid to solid. Table 3.2.1 gives the latent heat of fusion for some common substances. Latent heat of fusion has the units of $J\,kg^{-1}$.

specific latent heat of fusion
the heat required to change the state of 1 kg of a substance from a solid to a liquid without a change in temperature

The specific latent heat of vaporisation

The specific latent heat of vaporisation of a substance is the heat required to change the state of 1 kg of the substance from its liquid to gaseous state. The specific latent heat of vaporisation of water is $2260\,kJ\,kg^{-1}$. You can see from the very large value that it requires a huge amount of energy to separate the particles from each other. This is the same amount of energy that is released when 1 kg of the same substance condenses from gas to liquid. Table 3.2.1 also shows the latent heat of vaporisation for some common substances.

specific latent heat of vaporisation
the heat required to change the state of 1 kg of a substance from a liquid to a gas without a change in temperature

TABLE 3.2.1 Latent heats of fusion and vaporisation for a number of common substances. Unlike specific heat, $J\,kg^{-1}K^{-1}$, latent heat is given in $kJ\,kg^{-1}$.

SUBSTANCE	SPECIFIC LATENT HEAT OF FUSION ($kJ\,kg^{-1}$)	SPECIFIC LATENT HEAT OF VAPORISATION ($kJ\,kg^{-1}$)
Aluminium	390	10 500
Alcohol (ethanol)	105	841
Copper	205	4 800
Iron	276	6 340
Lead	25	860
Silver	105	2 350
Water	334	2 260

3.2.1 Change of state and latent heat

Investigating latent heat

The concept of latent heat can be described in the following example.

Students completed an investigation in which they heated different masses of ice at 0°C that had been dried to remove any liquid water from its surface. The heat energy was supplied at a steady rate of $1000\,J\,s^{-1}$ until the ice had just melted. The time was recorded and precautions were taken to minimise any external heat gains or losses. The data were recorded in Table 3.2.2, and graphed in Figure 3.2.1 (page 70).

INQUIRING FURTHER

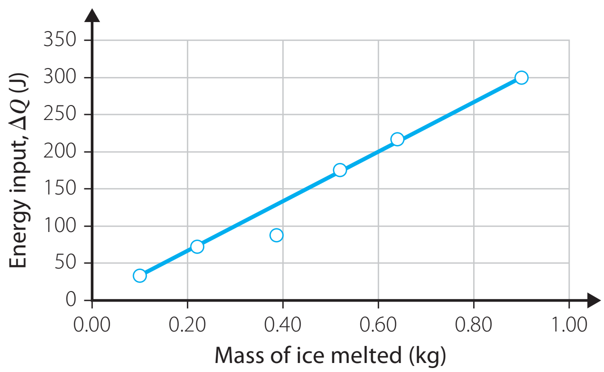
The specific latent heat of vaporisation of water is high relative compared to its specific heat capacity. When water evaporates, it absorbs heat, which must be released to the atmosphere when it condenses again as clouds. This heat has profound effects on the development of storm systems.

Investigate the role of the latent heat of vaporisation in weather systems.

TABLE 3.2.2 Data from student investigation

MASS OF ICE AT 0°C (g)	TIME FOR MELTING (s)	TOTAL ENERGY INPUT (kj)
0.10	33	33
0.22	72	72
0.39	88	88
0.52	175	175
0.64	217	217
0.90	300	300

FIGURE 3.2.1 Finding the relationship between energy input and mass of ice melted. The equation of the line is $Q = m \times 334$.



The graph indicates that there is a direct proportionality. In general:

$$Q \propto m$$

There is always a constant that makes a proportionality an equality; in this case L is used as the constant:

$$Q = Lm$$

Rearranging the equation gives:

$$L = \frac{Q}{m}$$

L, the specific latent heat, is the gradient of the graph.

Units of $L = \frac{\text{J}}{\text{kg}} = \text{J kg}^{-1}$

This gives the algebraic expression of the relationship between state changes and energy required to change the state.

KEY FORMULA

The latent heat equation

$Q = mL$

Where:

Q = heat required or released during a state change

m = mass of the object undergoing the state change

L = specific latent heat of the substance and state change

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SECTION REVIEW 3.2

REMEMBERING

1 Define:
   a latent heat
   b specific latent heat of fusion
   c specific latent heat of vaporisation.

UNDERSTANDING

2 Rank the substances listed in Table 3.2.1 (page 69) in order of increasing latent heat of vaporisation. Discuss what this says about the heat required to boil 1 kg of water as compared to the amount of heat required to boil 1 kg of aluminium.

3 If 205 kJ of energy is released when 1.0 kg of liquid copper at its melting point fully solidifies into solid copper, how much energy would be released if 3.0 kg of liquid copper at the same temperature were to fully solidify?

3.3 Solving problems: specific latent heat

The specific latent heat, L in the latent heat equation, is specific and unique for every substance and every type of phase change. It can be replaced with L_f, the specific latent heat of fusion, if the substance is undergoing a phase change between solid and liquid, and L_v, the specific latent heat of vaporisation, if the state change is between liquid and gas.

$$L_f = \text{latent heat of fusion}$$

$$L_v = \text{latent heat of vaporisation}$$

When solving problems involving the latent heat equation, it is once again important to make sure that all variables have standard SI units.

WORKED EXAMPLE 3.3.1

How much heat must be added to 15 g of solid tungsten at its melting point to completely liquefy it? Tungsten has a latent heat of fusion of 44 kcal kg^{-1}.

ANSWER

Convert 44 kcal kg^{-1} to J kg^{-1}:

$$44\frac{\text{kcal}}{\text{kg}} \times \frac{4186\text{ J}}{1\text{ kcal}} = 184\,184\text{ J kg}^{-1} \quad (1)$$

Use the specific latent heat of vaporisation equation:

$$Q = mL_v \quad (2)$$

Substitute equation (1) into equation (2):

$Q = 0.015\text{ kg} \times 184\,184\text{ J kg}^{-1}$

Calculate the answer:

$Q = 2762.76\text{ J}$

Use the correct number of significant figures:

$Q = 2700\text{ J}$

2700 J of heat must be added.

WORKED EXAMPLE 3.3.2

If 250 g of gaseous chlorine at its boiling temperature releases 1.44×10^5 J of energy when it liquefies, calculate the specific latent heat of vaporisation for chlorine gas. Give the answer in kJ kg^{-1}.

ANSWER

Apply the specific latent heat of vaporisation equation since condensation is involved:

$Q = mL_v$

Rearrange for the required unknown:

$$L_v = \frac{Q}{m}$$

Insert the known values:

$$L_v = \frac{1.44 \times 10^5 \text{ J}}{0.25 \text{ kg}}$$

Calculate the answer:

$L_v = 576\,000 \text{ J kg}^{-1}$

Give the answer with the correct units and number of significant figures:

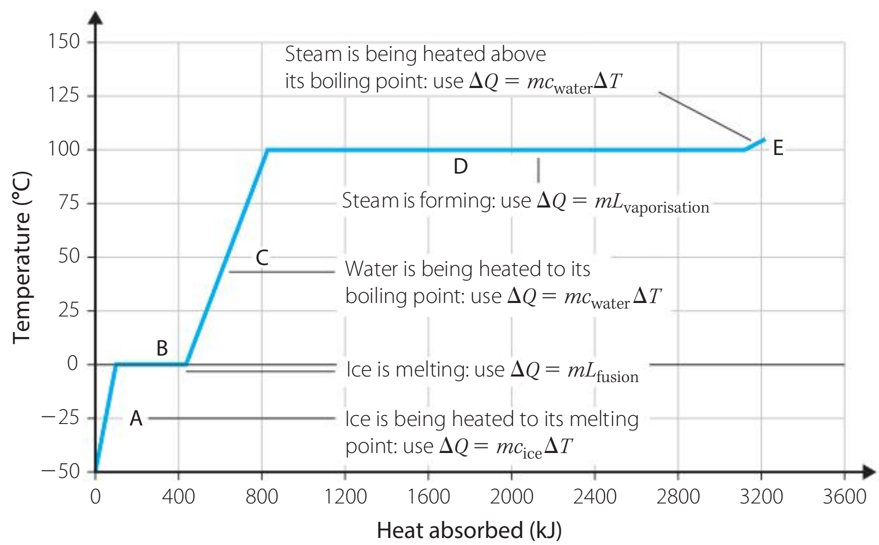
$L_v = 580 \text{ kJ kg}^{-1}$

Solving for multiple temperature and state changes

Many real-life situations involve temperature and state changes occurring in a process that is being studied; for example, cooling down a hot barbecue plate with water and perspiring to remove excess heat from your body both involve liquid to gas phase changes. The heating curve of a substance becomes a very handy tool when solving problems that involve multiple temperature and state changes.

Different sections of the curve require different calculations to find the energy input needed to heat and change the temperature or state of ice, water or steam. Cooling requires the release to the surroundings of the same amounts of energy. The calculations used depend on whether the water remains in its state or its state is changing.

FIGURE 3.3.1 The heating curve for 1 kg of pure water



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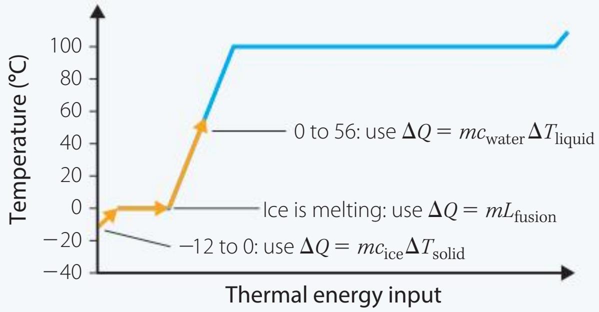
WORKED EXAMPLE 3.3.3

A 430.0 g sample of ice at −12°C is heated to water at 56°C.

a Sketch the heating curve for water and identify the section of the curve that the problem covers.
b How much thermal energy is required?

ANSWERS

a



b Use the latent heat and the specific heat formulas together since the problem involves a phase change and a change in temperature:

$Q_{total} = mc_{ice}\Delta T_{solid} + mL_f + mc_{water}\Delta T_{liquid}$

Insert the known values:

$Q_{total} = [0.430\,\text{kg} \times 2.10 \times 10^3\,\text{J}\,\text{kg}^{-1}\text{K}^{-1} \times (0 - {}^{-}12)] + (0.430\,\text{kg} \times 3.34 \times 10^5\,\text{J}\,\text{kg}^{-1}) + (0.430\,\text{kg} \times 4.2 \times 10^3\,\text{J}\,\text{kg}^{-1}\text{K}^{-1}) \times (56 - 0)$

Calculate the answer:

$Q_{total} = 255\,592\,\text{J}$

Give the answer with the correct number of significant figures:

$Q_{total} = 2.6 \times 10^3\,\text{kJ}$

PRACTICAL ACTIVITY 3.3.1

Phase changes

The fact that the temperature of a material does not change during a phase change despite heat being added can seem counterintuitive. During this experiment, you will investigate the temperature change of ice during a phase change to verify this claim.

AIM

To observe the changes in temperature that a sample of ice undergoes before, during and after a phase change into liquid water

MATERIALS

- calorimeter
- immersion heater
- thermometer or calibrated temperature probe
- electronic scales

»

- sample of crushed ice
- power supply
- stopwatch

Add any other risks that you can think of and ways to manage them.

RISK ASSESSMENT

WHAT ARE THE RISKS IN DOING THIS EXPERIMENT?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
Heating equipment can cause burns.	Avoid touching the equipment. Wait for the equipment to cool before you put it away.
Electrical equipment may cause shocks or electrocution	Double-check that all electrical equipment is in good working order. Avoid touching the electrical equipment while it is being used.

PROCEDURE

1. Place the crushed ice, thermometer and heating element into the calorimeter, ensuring that the heating element and thermometer are not in contact either with each other or with the walls of the calorimeter.
2. Measure the temperature of the ice and record this and any observations that you have in the 0 minutes row of the table below.
3. Connect the heating element to the power supply and turn the power on.
4. After 2 minutes, record the temperature of the sample and your observations.
5. Continue measuring the temperature and making observations at 2-minute intervals, making sure to stir the contents just before taking your measurements.
6. Continue to record your data until the temperature of the sample is 5°C above the point at which it completely liquefied.

RESULTS

Experimental results

Time (s)	0	120	240	360	480	600	720	840	960	1080	1200	1320	1440	1560	1680	1800
Temperature (°C)																

ANALYSIS OF RESULTS

Construct a graph from your experimental data.

DISCUSSION

1. What did your observations of the physical state of the ice reveal as it went through its phase transition?
2. What happened to the temperature of the sample before, during and after the phase change?
3. Why does the temperature of the sample remain constant during the phase change?
4. How could you improve the experiment to obtain more precise data?
5. What other substances could you investigate?
6. How could you refine the experiment to be able to measure the latent heat of fusion of water?

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SECTION REVIEW 3.3

REMEMBERING

1 Identify the correct units of each of the following variables:

a Heat added, Q

b Mass, m

c Specific latent heat, L.

2 For each of the following scenarios, state whether you would use the latent heat of fusion L_f or the latent heat of vaporisation L_v.

a Ice becomes liquid water.

b Steam becomes liquid water.

c Liquid water becomes ice.

d Liquid water becomes steam.

APPLYING

3 How much heat is required to completely melt 330 g of solid silver that is at its melting point?

4 If it takes 52.8 kcal to vaporise a 160 g sample of liquid ammonia that is at its boiling point, what is the latent heat of vaporisation of ammonia?

5 A 3.2 kg sample of copper is at 975°C and is heated until it completely liquefies at its melting point of 1085°C.

Sketch the heating curve of copper for the temperature region that the problem covers.

6 A scientist would like to obtain 2.5 kg of liquid nitrogen at −210°C from an equal amount of nitrogen gas at 25°C. How much energy must be removed from the gas to achieve this if the boiling point of nitrogen is −210°C? ($c_N = 0.248\,\text{kcal}\,\text{kg}^{-1}\,°\text{C}^{-1}$ and $L_{v,N} = 199\,\text{kJ}\,\text{kg}^{-1}$)

7 A 330 g sample of ice is heated until it completely vaporises as steam.

a Sketch the heating curve of water that covers the temperature range of the problem.

b How much heat must be added for the ice to become steam?

CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 Define the following terms.
   a Phase change
   b Melting
   c Solidification
   d Vaporisation
   e Condensation
   f Sublimation
   g Deposition
   h Evaporation
   i Latent heat
   j Specific latent heat of fusion
   k Specific latent heat of vaporisation

2 Explain what happens to the temperature of a substance as it undergoes a phase change.

CATEGORY QUESTIONS

3 Distinguish between vaporisation and evaporation.

4 Explain what happens on a particle level before, during and after a solid object undergoes a phase change into a liquid when heat is added to it.

ELABORATION QUESTIONS

5 Use the kinetic particle model to explain why the temperature of an object decreases when it is undergoing evaporative cooling.

6 Explain why the temperature of a substance remains constant during a phase change.

EVIDENCE QUESTIONS

7 Given enough time, what would be the result of extended evaporative cooling on a liquid substance? Identify at least 2 situations where this is used.

8 Identify two to three instances where two phases exist in a sample at the same time? How does this give evidence to support the claim that the temperature of a substance remains constant during a phase change?

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END-OF-CHAPTER EXAM

End-of-chapter test

PHYSICS

1 Which of the following processes does not result in particles of a liquid entering a different phase?

A Solidification
B Vaporisation
C Deposition
D Evaporation

2 What happens to the temperature of a liquid during evaporation?

A It increases.
B It stays the same.
C It decreases.

3 The latent heat of a phase change is dependent upon:

A the mass of the substance.
B the electrical conductivity of a substance.
C the temperature change undergone by the substance.
D the surface area of the substance.

4 Which of the following is the SI unit for the specific latent heat of vaporisation?

A $J\,°C^{-1}$
B $cal\,kg^{-1}$
C $J\,kg^{-1}$
D $cal\,kg^{-1}\,°C^{-1}$

5 What is the name of the phase change that occurs when a gas changes directly into a solid without going through the liquid phase?

6 Define 'evaporation'.

7 Define 'specific latent heat'.

8 Calculate the amount of heat that is released when 3.5 kg of steam condenses to liquid water.

9 Calculate the mass of copper that would liquefy if 135 kJ of heat is added.

10 Explain in terms of the kinetic particle theory what happens when a substance undergoes a change from the liquid phase to the solid phase.

11 Explain what happens when a pocket of moist air surrounded by dry air rises into the atmosphere.

12 Calculate the amount of heat energy that would be required to completely vaporise 0.50 kg of liquid ethanol at 25°C, given that the boiling point of ethanol is 78°C.

13 Calculate the mass of ice transformed, when 380 kJ of heat in total is used to transform solid ice at −12°C to liquid water at 56°C.

14 An electric hotplate is used to heat a 1.6 kg block of ice at 0°C to steam at 100°C. If it takes 10 minutes to boil the water away and 15% of the heat generated by the hotplate is lost to the surroundings, calculate the power rating of the hotplate.

4 ENERGY CONSERVATION IN CALORIMETRY

Introduction

So far we have investigated the thermodynamic behaviour of objects when heat is added to them during a phase change and between phase changes. But where does this energy come from or go to?

Naturally, it must have come from another object.

In this chapter, we will investigate the thermodynamics of mixtures, both from a conceptual and a mathematical perspective, and what happens when two objects are placed into thermal contact and heat is transferred between them.

Stimulus questions

Why do objects spontaneously come to the same temperature when they are mixed?

Do objects at the same temperature exchange energy?

Does putting a coat on a snowman make it melt faster?

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4.1 Thermal equilibrium and the energy of particles

Two objects at different temperatures will eventually reach the same temperature when they are put into thermal contact (when thermal energy can transfer between them). For example, if you place a hot stone in a container of cold water, heat energy is transferred from the hot stone to the cold water and container. The heat lost by the stone is equal to the heat gained by the water and the container. The stone gets cooler and the water and its container get warmer. This transfer will continue until both reach the same temperature. They are now said to be in **thermal equilibrium**.

thermal equilibrium the condition in which two or more objects in physical contact have the same temperature and average kinetic energy as each other

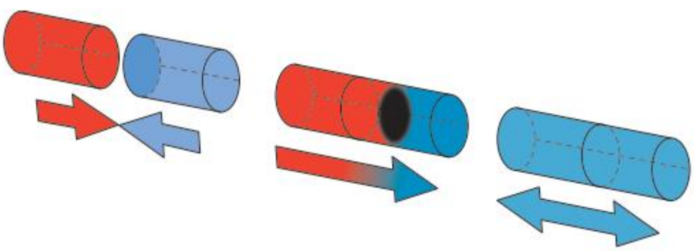


FIGURE 4.1.1 Hot and cold objects reach thermal equilibrium due to the transfer of energy by particle collisions. Eventually, the average kinetic energy of particles in the two objects is the same.

When they are at thermal equilibrium, heat is still being transferred between the water particles and the stone particles; however, the amount of heat going from the water into the stone exactly balances the amount of heat leaving the stone and going into the water. There is no longer a net transfer of heat from one to the other. Therefore, another condition necessary to be able to state that two objects are in thermal equilibrium is that there is no net transfer of energy between them.

INQUIRING FURTHER

If the fact that when objects are placed in thermal contact they will reach thermal equilibrium is taken to its logical conclusion, then, given enough time, all the particles in the universe will reach the same temperature, and energy can no longer be transferred between them. This is known as the heat death of the universe. Explore this theory and investigate evidence to support or refute it.

SECTION REVIEW 4.1

REMEMBERING

1 Describe the temperature condition for two objects if they are in thermal equilibrium.

2 Describe the energy condition for two objects if they are in thermal equilibrium.

UNDERSTANDING

3 Explain in terms of heat flow what happens when an ice tray full of liquid water is placed in the freezer compartment of a refrigerator.

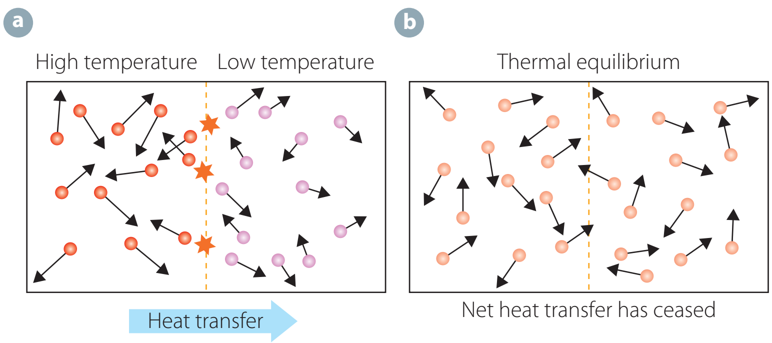
4 Explain what happens in terms of heat flow when an ice tray full of solid ice is taken out of the freezer and placed on the counter in a room at 25°C.

4.2 Achieving thermal equilibrium

Recall that the temperature of an object is a measure of the average kinetic energy of the particles in a system. When two objects of different temperature are placed in thermal contact, the kinetic energy of the particles in the hotter object begins to be transferred into the colder object through the process of elastic collisions between the particles. This continues until the average kinetic energy of the two objects is equal.

In the case of a pot of water on a stove, the particles of the hot element have a large average kinetic energy. At the boundary with the saucepan they undergo collisions with the particles of the pan and transfer some of this kinetic energy to them, causing the temperature of the saucepan to increase until the particles of the pan and the element have the same average kinetic energy. The same process occurs at the boundary between the saucepan and the water. This can be seen in Figure 4.2.1(a).

FIGURE 4.2.1 The particles of two substances collide when **(a)** they are at different temperatures when heat is being transferred, and **(b)** at thermal equilibrium when no net heat is transferred.



SYLLABUS LINK
Chapter 1 discusses the first and second laws of thermodynamics.

zeroth law of thermodynamics if two systems are in thermal equilibrium with a third system, then they must be in thermal equilibrium with each other

Once the particles of both objects have the same average kinetic energy, they must have the same temperature and are therefore in thermal equilibrium. Collisions between particles of the two systems still occur, with a concurrent transfer of kinetic energy; however, the likelihood of the particles in the saucepan transferring kinetic energy to the particles of the stove element is equal to the likelihood of the particles in the stove element transferring energy to the particles in the saucepan. This is why there is no net heat flow between objects at thermal equilibrium. This can be seen in Figure 4.2.1(b).

Experiments have shown that if two systems are in thermal equilibrium with a third system, then they must be in thermal equilibrium with each other. This observation is the basis of the **zeroth law of thermodynamics**. This unusual name is a result of the fact that it was not until scientists had worked out the first and second laws of thermodynamics that they realised that this obvious law needed to be defined.

As well as being a measure of the average kinetic energy of an object, temperature is also a property that determines whether an object is in thermal equilibrium with other objects. If two systems are in thermal equilibrium, then they must have the same temperature and no net thermal energy will flow between them. The importance of the zeroth law is, therefore, that it gives a useful definition of temperature that agrees with our everyday experience that when a hot object and a cold object are put into contact, they will eventually reach the same temperature.

SECTION REVIEW 4.2

UNDERSTANDING

1. Explain, using the kinetic particle model, how two objects at thermal equilibrium maintain equal temperatures if their particles are still colliding and transferring kinetic energy.
2. Explain, on a particle level, what happens when an ice tray full of liquid water is placed in the freezer compartment of a refrigerator.
3. Explain, on a particle level, what happens when an ice tray full of solid ice is taken out of the freezer and placed on the counter in a room at 25°C.
4. Explain what is happening on a particle level when a saucepan of cold water is placed on a hot stove element.
5. A bottle of water is at thermal equilibrium with the air in a room and is also at thermal equilibrium with the benchtop on which it is standing. Compare the kinetic energy of the particles of all three objects.

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4.3 Solving problems: thermal equilibrium and the spontaneous transfer of heat

When solving problems involving thermal equilibrium and the spontaneous transfer of heat between objects as they approach thermal equilibrium, scientists often speak about specific systems. A **system** can be considered as any object or set of objects that we are investigating. There are several different types of systems.

system
any object or set of objects under investigation

Open, closed and isolated systems

An **open system** is any system in which mass and energy can enter or leave. Most real-life systems would be considered open. Many idealised systems that are studied in physics are said to be **closed systems** – systems in which no mass can enter or leave (but from which energy can be transferred). A closed system is said to be an **isolated system** if no mass or energy can cross its boundaries.

open system
a system that can lose mass and energy to its surroundings

closed system
a system that can lose energy but not mass to its surroundings

isolated system
a system in which no matter or energy transfers into or out and in which no energy is created or destroyed

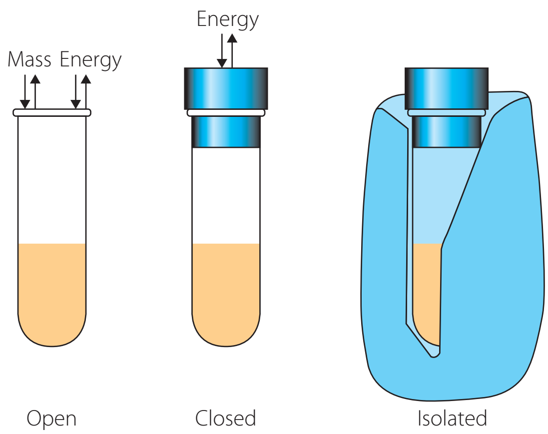

FIGURE 4.3.1 Open, closed and isolated systems

When studying real-life situations involving heat flow, it is often the case that we need to include the source of the heat and the temperature and phase changes that it undergoes in our calculations as well as the heat flow in or out and the resultant temperature and state changes.

It is often useful to consider many systems in thermodynamics as being isolated and therefore the law of conservation of energy can be applied. The first law of thermodynamics (the law of conservation of energy) states that in an isolated system, energy can neither be created nor destroyed. Energy can be transferred or transformed, but the total energy of an isolated system remains constant. The total change in energy is zero. Therefore, if an isolated system contains two parts that are at different temperatures and all of the heat energy from the hotter object is transferred into kinetic energy of the particles of the colder substance, then it can be assumed that the heat lost by one object is equal to the heat gained by the other.

For example, when a barbecue plate is cooled down by throwing ice on it, all the heat that is released by the hot plate will be absorbed by the ice, which will turn to water, continue to absorb heat as a liquid and, most likely, turn into steam.

KEY FORMULA

Heat transfers in an isolated system

$Q_{lost} = Q_{gained}$

Where:

Q_{lost} = heat lost by objects in the system

Q_{gained} = heat gained by objects in the system

WORKED EXAMPLE 4.3.1

If 350 g of water at 10°C is added to 0.40 kg of water at 75°C, what final temperature will the mixture reach?

ANSWER

Assume the hot and cold water are an isolated system, so:

heat lost by hot water = heat gained by cold water

Apply conservation of energy:

$$-Q_{hot} = Q_{cold}$$

Apply the specific heat equation (it can be assumed there will be no phase changes):

$$-m_{hot}c\Delta T_{hot} = m_{cold}c\Delta T_{cold}$$

Cancel the c on both sides, since they are identical (water) and multiply both sides by −1:

$$m_{hot}\Delta T_{hot} = -m_{cold}\Delta T_{cold}$$

Expand ΔT on both sides, noting that T_{final} is the same for both:

$$m_{hot}(T_{final} - T_{initial,\,hot}) = -m_{cold}(T_{final} - T_{initial,\,cold})$$

Expand the brackets on both sides:

$$m_{hot}T_{final} - m_{hot}T_{initial,\,hot} = -m_{cold}T_{final} + m_{cold}T_{initial,\,cold}$$

Gather the like term T_{final} on one side of the equation:

$$m_{hot}T_{final} + m_{cold}T_{final} = m_{cold}T_{initial,\,cold} + m_{hot}T_{initial,\,hot}$$

Factorise T_{final} on the left-hand side:

$$(m_{hot} + m_{cold})T_{final} = m_{cold}T_{initial,\,cold} + m_{hot}T_{initial,\,hot}$$

Leave T_{final} as the subject:

$$T_{final} = \frac{m_{cold}T_{initial,\,cold} + m_{hot}T_{initial,\,hot}}{m_{hot} + m_{cold}}$$

Substitute known values:

$$T_{final} = \frac{0.35\text{ kg} \times 10°\text{C} + 0.4\text{ kg} \times 75°\text{C}}{0.4\text{ kg} + 0.35\text{ kg}}$$

Calculate the answer:

$$T_{final} = 44.66667°\text{C}$$

Give the answer to the correct number of significant figures:

$$T_{final} = 45°\text{C}$$

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WORKED EXAMPLE 4.3.2

250 g of boiling hot coffee (100.0°C) is poured into a 150 g copper cup initially at 30.0°C. What will be the final temperature of the coffee and the cup?

ANSWER

heat lost by coffee = heat gained by cup

Assume coffee and coffee cup are an isolated system and apply the conservation of energy equation:

$$Q_{coffee} = -Q_{cup}$$

Apply the specific heat equation to both sides as there is no phase change:

$$m_{coffee}c_{coffee}\Delta T_{coffee} = -m_{cup}c_{cup}\Delta T_{cup}$$

Substitute known values and use T_{final} as the final temperature for both:

$$(0.25\,\text{kg})\left(4180\frac{\text{J}}{\text{kg}\,°\text{C}}\right)(T_{final} - 100°\text{C}) = -(0.15\,\text{kg})\left(380\frac{\text{J}}{\text{kg}\,°\text{C}}\right)(T_{final} - 30°\text{C})$$

Expand the brackets:

$$(1045\,\text{J}\,°\text{C}^{-1})T_{final} - 104\,500\,\text{J} = -(57\,\text{J}\,°\text{C}^{-1})T_{final} + 1710\,\text{J}$$

Put all terms containing the unknown T_{final} on the left-hand side:

$$(1045\,\text{J}\,°\text{C}^{-1})T_{final} + (57\,\text{J}\,°\text{C}^{-1})T_{final} = 1710\,\text{J} + 104\,500\,\text{J}$$

Factorise T_{final}:

$$(1102\,\text{J}\,°\text{C}^{-1})T_{final} = 106\,210\,\text{J}$$

Calculate the answer:

$$T_{final} = 96.380°\text{C}$$

Use the correct number of significant figures:

$$T_{final} = 96°\text{C}$$

WORKED EXAMPLE 4.3.3

A nurse prepares a bath that needs to be at 41°C for a patient. First he adds 53 L of water at 23°C from the cold tap.

a What four assumptions must be made to calculating part **b**?

b How much water does he need to add from the hot tap at 68°C for him to achieve the required of temperature of 41°C?

ANSWERS

a Assumptions:

1. No energy is lost to the surroundings such as the taps, the air and the bath.
2. The mixing process does not add energy to the water.
3. The water is pure.
4. 1 L of water has a mass of 1 kg.

b Assume it is an isolated system and apply the conservation of energy equation:

$$Q_{hot} = -Q_{cold}$$

Apply the specific heat equation to both sides:

$$m_{hot}c\Delta T_{hot} = -m_{cold}c\Delta T_{cold}$$

Make m_{hot} the subject:

$$m_{hot} = \frac{-m_{cold}c\Delta T_{cold}}{c\Delta T_{hot}}$$

Cancel c as it is common (water):

$$m_{hot} = \frac{-m_{cold}\Delta T_{cold}}{\Delta T_{hot}}$$

Substitute known values:

$$m_{hot} = \frac{-53\text{ kg} \times (41°\text{C} - 23°\text{C})}{(41°\text{C} - 68°\text{C})}$$

Calculate the answer:

$$m_{hot} = 35.3\text{ kg}$$

Give the answer to the correct number of significant digits:

$$m_{hot} = 35\text{ kg}$$

The nurse needs to add 35 kg or 35 L of hot water.

WORKED EXAMPLE 4.3.4

Two 50.0 g ice cubes at 0.0°C are placed into a full 3.0 L jug of 25°C water. Calculate the final temperature of the mixture.

ANSWER

Assume it is an isolated system and apply the conservation of energy equation:

$$Q_{ice} = -Q_{water}$$

Apply the specific heat and latent heat equations since the ice will undergo a phase change:

$$m_{ice}L_{f,\,ice} + m_{ice}c_{water}\Delta T_{water} = -m_{water}c_{water}\Delta T_{water}$$

Insert known values (3 L of water = 3 kg) and expand T_{final} on both sides:

$$0.1\text{ kg} \times 334\,000\text{ J kg}^{-1} + 0.1\text{ kg} \times 4180\text{ J kg}^{-1}\,°\text{C}^{-1}(T_{final} - 0°\text{C}) = -3\text{ kg} \times 4180\text{ J kg}^{-1}\,°\text{C}^{-1}(T_{final} - 25°\text{C})$$

Expand the brackets:

$$33\,400\text{ J} + 418\text{ J }°\text{C}^{-1} \times T_{final} = -12\,540\text{ J }°\text{C}^{-1} \times T_{final} + 313\,500\text{ J}$$

Gather terms containing T_{final} on the left and factorise:

$$(418\text{ J }°\text{C}^{-1} + 12\,540\text{ J }°\text{C}^{-1})T_{final} = 313\,500\text{ J} - 33\,400\text{ J}$$

$$12\,958\text{ J }°\text{C}^{-1} \times T_{final} = 280\,100\text{ J}$$

$$T_{final} = \frac{280\,100\text{ J}}{12\,958\text{ J C}^{-1}}$$

Calculate the answer:

$$T_{final} = 21.616°\text{C}$$

Give the answer to the correct number of significant digits:

$$T_{final} = 22°\text{C}$$

The final temperature of the mixture is 22°C.

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WORKED EXAMPLE 4.3.5

A 2.5 kg iron barbecue plate at 328°C is too hot for cooking and needs to be cooled to 200°C. If this is to be done by placing a block of ice on the plate, how much ice at 0°C will be required?

ANSWER

If the final temperature is to be 200°C and only just enough ice is to be used to achieve this heat transfer, the particles of ice will go through the melting phase change, through the entire liquid phase, and finally through the vaporisation phase change. Once again, we will assume the system is isolated and therefore all the heat absorbed by the ice in its transformation will come from the heat lost by the iron (Fe).

Assume it is an isolated system and apply the conservation of energy equation:

$$Q_{Fe} = -Q_{ice}$$

This problem will be easier to solve if the negative is on the left, because the heat lost by iron will have only one term:

$$-Q_{Fe} = Q_{ice}$$

The ice will turn to steam, so apply the latent heat of fusion and the latent heat of vaporisation equations together with the specific heat equations:

$$-m_{Fe}c_{Fe}\Delta T_{Fe} = m_{ice}L_f + m_{water}c_{water}\Delta T_{water} + m_{water}L_v$$

Mass of ice and water is the same:

$$-m_{Fe}c_{Fe}\Delta T_{Fe} = m_{ice}(L_f + c_{water}\Delta T_{water} + L_v)$$

Make m_{ice} the subject:

$$m_{ice} = \frac{-m_{Fe}c_{Fe}\Delta T_{Fe}}{L_f + c_{water}\Delta T_{water} + L_v}$$

Insert known values:

$$m_{ice} = \frac{-2.5\text{ kg} \times 450\text{ J kg}^{-1}(200°\text{C} - 328°\text{C})}{3.34 \times 10^5\text{ J kg}^{-1} + 4.18 \times 10^3\text{ J kg}^{-1}\,{}^\circ\text{C}^{-1} \times (100°\text{C} - 0°\text{C}) + 2.26 \times 10^6\text{ J kg}^{-1}}$$

Calculate the answer:

$$m_{ice} = 0.047\,808\text{ kg}$$

Give the answer to the correct number of significant digits:

$$m_{ice} = 4.78 \times 10^{-2}\text{ kg}$$

The calorimeter

The experimental device called a calorimeter, which was introduced in the last chapter, is a way in which scientists can simulate the conditions of an isolated system. It uses a highly insulating material to ensure that almost no heat is lost to the environment. This is similar in design to the Dewar flask, described in Chapter 1 (page 14). A major use of the calorimeter is to determine the unknown specific heat capacity of a substance by immersing the substance at a known temperature in cooled water in the calorimeter. Since the heat lost by the substance will be gained by the water and the calorimeter, by measuring the final temperature of the water (which is the same as the substance and the calorimeter), the specific heat capacity of the substance can be found.

4.3.1 Calorimeters and calorimetry

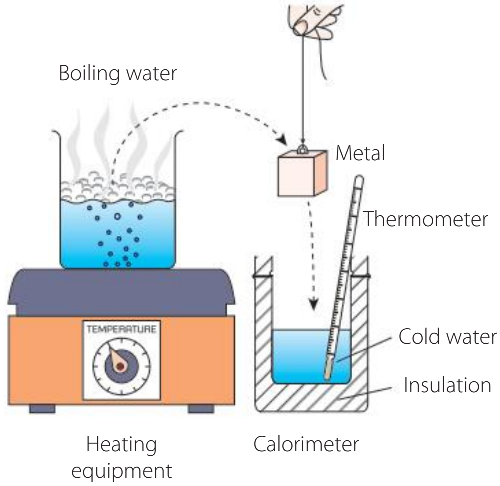

FIGURE 4.3.2 A calorimeter is used to calculate the unknown specific heat capacity of a substance.

WORKED EXAMPLE 4.3.6

A chemical engineer wants to determine the specific heat capacity of a 150 g sample of an unknown substance. To do this he initially heats the alloy to 540°C by placing it into a hot water bath. He then quickly removes it from the bath, dries it and places it into 400.0 g of water at 10.0°C ,which is held in a 250 g aluminium calorimeter. The final temperature of the system is 30.5°C. Calculate the specific heat of the unknown substance.

ANSWER

The system is isolated:

heat lost by substance = (heat gained by water) + (heat gained by calorimeter)

Apply the conservation of energy equation:

$$Q_{solid} = -(Q_{water} + Q_{cal})$$

The problem will be easier to solve if the negative is on the left-hand side:

$$-Q_{solid} = Q_{water} + Q_{cal}$$

Apply the latent and specific heat equations:

$$-m_S c_S \Delta T_S = m_W c_W \Delta T_W + m_{cal} c_{cal} \Delta T_{cal}$$

Rearrange for the unknown:

$$c_S = \frac{m_W c_W \Delta T_W + m_{cal} c_{cal} \Delta T_{cal}}{-m_S \Delta T_S}$$

Insert known values:

$$c_S = \frac{(0.4\ \text{kg})\left(4180\ \frac{\text{J}}{\text{kg°C}}\right)(30.5°\text{C} - 10.0°\text{C}) + (0.2\ \text{kg})\left(900\ \frac{\text{J}}{\text{kg°C}}\right)(30.5°\text{C} - 10.0°\text{C})}{-(0.15\ \text{kg})(30.5°\text{C} - 540°\text{C})}$$

Simplify:

$$c_S = \frac{34276\ \text{J} + 3690\ \text{J}}{76.425\ \text{kg°C}}$$

Calculate the answer:

$c_S = 496.77\,\mathrm{J\,kg^{-1}\,°C^{-1}}$

Give the answer to the correct number of significant figures:

$c_S = 5 \times 10^2\,\mathrm{J\,kg^{-1}\,°C^{-1}}$

The specific heat of the unknown substance is $5 \times 10^2\,\mathrm{J\,kg^{-1}\,°C^{-1}}$.

SECTION REVIEW 4.3

REMEMBERING

1 Describe the structure and thermodynamic properties of a calorimeter.

2 Explain why the equation $Q_{\mathrm{lost}} = -Q_{\mathrm{gained}}$ is another way of writing the conservation of energy principle.

UNDERSTANDING

3 Compare the thermodynamic properties of the following three types of systems.

- **a** Open
- **b** Closed
- **c** Isolated

4 Classify the following systems as open, closed or isolated.

- **a** The universe
- **b** A saucepan with a lid
- **c** A lake of water
- **d** A saucepan of water
- **e** A thermos flask of hot water
- **f** Gas in a balloon

APPLYING

5 If 2.0 L of hot water at 65.0° C is added to 1.0 L of cold water at 10.0°C, at what temperature will the mixture reach thermal equilibrium?

6 A 5.0 L tub of water contains 3.0 L of water at 23°C. The tub is then filled to the top with hot water. The final temperature of the water in the tub is 26°C. Calculate the initial temperature of the hot water.

7 A 60 kg bushwalker suffering from hypothermia has an average body temperature of 33.5°C. When rescued, she is wrapped in a blanket and given two 310 mL cups of warm tea each at a temperature of 60.0°C. Calculate the maximum rise in the bushwalker's temperature due to the heat of the tea. ($c_{\mathrm{human\,body}} = 3.5 \times 10^3\,\mathrm{J\,kg^{-1}\,K^{-1}}$)

8 When a 1.23 kg sample of an unknown material at 98.0°C is added to a 150 g aluminium calorimeter containing 250 g of water at 10.0°C, the final temperature is observed to be 38.0°C. Calculate the specific heat of the unknown material and suggest what it might be.

9 When a cook pours 100.0 mL of water at 65°C into a 5.0 kg iron saucepan at 140°C, it is observed that all the water is converted to steam. What is the final temperature of the saucepan?

10 How much steam at 100°C must be added to 1.0 kg of ice at 0°C such that the final mixture consists of liquid water at 22°C?

CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 Define the following terms.
  a Thermal equilibrium
  b The zeroth law of thermodynamics
  c The second law of thermodynamics
  d Open system
  e Closed system
  f Isolated system

2 Explain what happens, in terms of heat transfer, when two objects reach thermal equilibrium.

CATEGORY QUESTIONS

3 Give an example of two everyday objects that work by reaching a state of thermal equilibrium.

4 Describe the state of thermal equilibrium in terms of the kinetic particle model of matter.

5 Give one example each for the following types of systems.
  a Open
  b Closed
  c Isolated

6 Compare the second law of thermodynamics to the state of thermal equilibrium and decide whether they are describing the same concept. Explain your opinion.

ELABORATION QUESTIONS

7 What does the zeroth law of thermodynamics imply for three objects that are all at the same temperature, in terms of their average kinetic energy and their internal energy?

8 Explain why it is not possible to solve thermal equilibrium problems for open and closed systems.

9 If the universe is an isolated system, explain what this means about the amount of energy in the universe at the time of the Big Bang and the amount of energy in the universe now.

10 If the universe is an isolated system, use the second law of thermodynamics to explain the predictions of the heat death of the universe.

EVIDENCE QUESTIONS

11 It is found that everything outside of a certain closed system is composed of a single object in an isolated system. Explain how the zeroth law of thermodynamics could be used to include the system and its surroundings as an isolated system.

12 Research the heat death of the universe to find evidence that either supports or refutes it.

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END-OF-CHAPTER EXAM

Qz End-of-chapter test

PHYSICS

1 Which of the following options is indicative of two objects at thermal equilibrium?

A They have different temperatures.

B There is a net heat flow from one object to the other.

C They have equal average kinetic energies.

D They have equal amounts of potential energy.

2 What type of system is the calorimeter an experimental example of?

A Open **B** Closed **C** Isolated

3 An open bottle of spring water is an example of what type of system?

A Open **B** Closed **C** Isolated

4 A closed bottle of spring water is an example of what type of system?

A Open **B** Closed **C** Isolated

5 Collisions between particles of two different objects allow what thermodynamic property to flow between them?

6 What form of energy is being equilibrated as two objects approach thermal equilibrium?

7 State the zeroth law of thermodynamics.

8 State the second law of thermodynamics.

9 If 150 mL of water at 12°C is mixed with 250 g of water at 45°C, what will be the final temperature of the mixture if no heat is lost to the environment?

10 0.20 L of water at 100°C is poured onto a 3.0 kg iron barbecue plate at 180°C. Calculate the final temperature of the hotplate once all of the water has vaporised, if it is assumed no heat is lost to the surroundings.

11 Explain how the first law of thermodynamics can be used when solving problems involving isolated systems.

12 Suppose that equal masses of lead and water are in thermal equilibrium. If the same amount of heat energy is added to each, will they still be in thermal equilibrium?

13 How much steam at 100°C must be added to 1.0 kg of ice at 0°C so that the final mixture consists of liquid water at 25°C?

14 Calculate the final temperature of the system when a 150 g iron ingot at 85°C is placed into a 250 mL sample of pure water in a 110 g aluminium calorimeter at 25°C.

5 ENERGY IN SYSTEMS – MECHANICAL WORK AND EFFICIENCY

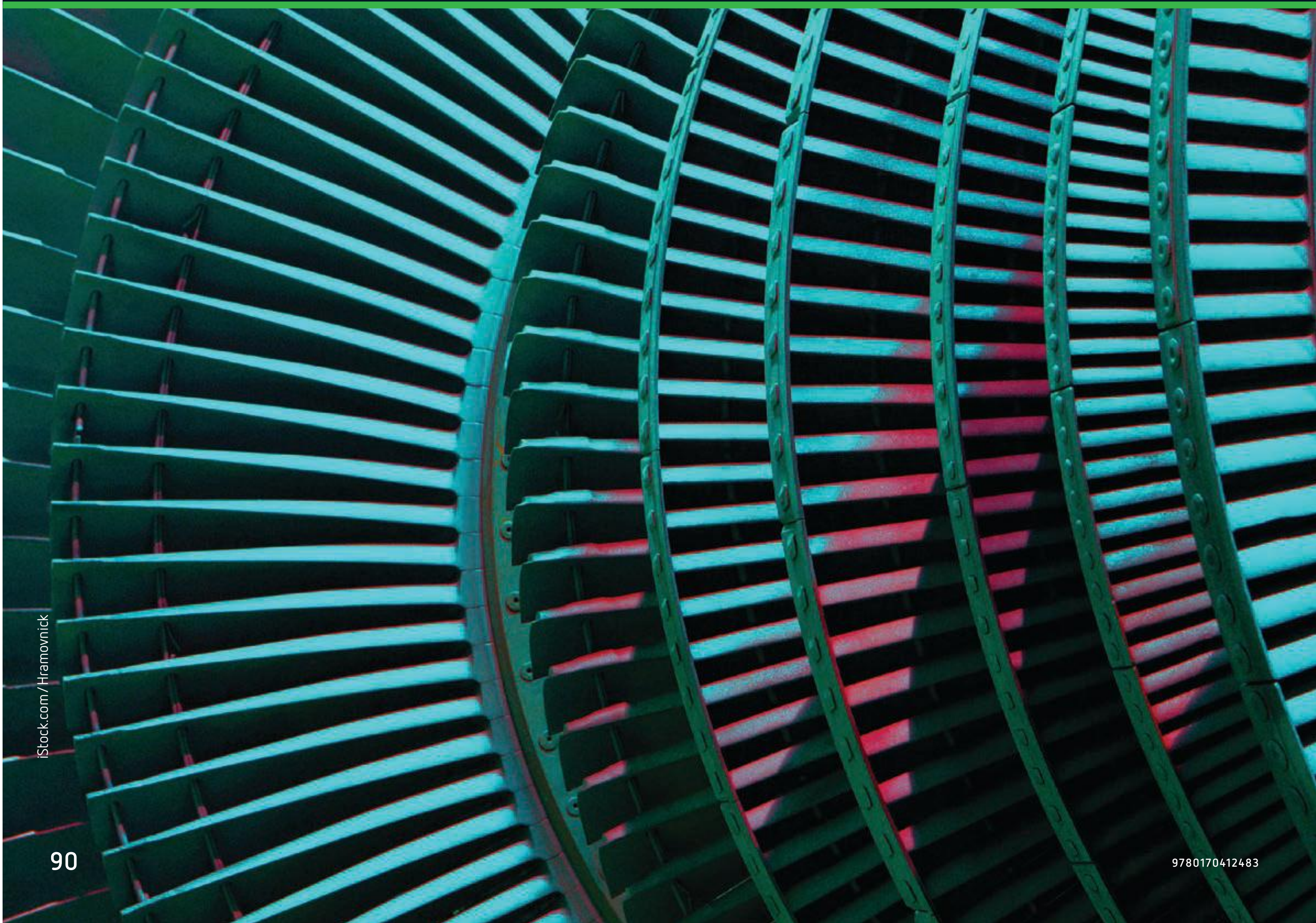
Introduction

The field of thermodynamics was developed in the 19th century as a direct result of the technological advancements of the industrial age. During this time of great invention, new industries across the globe were finding ways to utilise the energy held within objects to complete tasks that would previously have been carried out by hand.

In this chapter, we will investigate, from a physics standpoint, just how the world was changed forever by the fact that the internal energy of a substance can be used to perform useful work. In addition, we will explore the transformations that take place in some common engines and discuss factors that impact their efficiency.

Stimulus questions

- What is work?
- Where does the energy to power a car, a washing machine or an electrical turbine come from?
- Is it possible to produce a completely efficient engine?
- If usable energy is reduced every time an energy transfer occurs, what implications will this have on the availability of usable energy in the future?



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5.1 The capacity to do work

Heat is one way in which energy can be transferred from one object or system to another. The other way in which energy can be transferred to another object or system is through the action of a force. **Work**, W, is defined as the energy transferred by the action of a force over a distance. When a force, F, acts on an object and moves the object through some distance, s, in the same direction as the force, the energy transferred to the object is equal to:

$$W = F \times s$$

work
the energy transferred due to the action of a force over a distance

KEY FORMULA

Work defined

$W = F \times s$

Where:

W = work

F = force

s = distance

This equation calculates the work done by the object applying the force. But it can also show the work done on an object by the application of a force. Work has units of newton metres (N.m), which is equivalent to $kg\,m^2\,s^{-2}$. As work is a form of energy, this unit is also equivalent to the joule (i.e. 1 N.m = 1 J).

It is important to differentiate between heat and work, as they are both ways in which energy can be transferred. Remember that work is energy transferred by the action of a force while heat is energy transferred due to a temperature difference.

The rate at which energy is transferred, either by heat or work, is called power. Power, P, is energy, E, transferred per unit time. If the only energy transferred is in the form of work, then this can also be written as the work, W, performed per unit time:

KEY FORMULA

$$P = \frac{E}{t} = \frac{W}{t}$$

Where:

P = power

E = energy transferred

t = time

W = work

5.1.1 How does work work?

Power has the unit of $J\,s^{-1}$, which is given the name watt (W) after the Scottish engineer James Watt (1736–1819), who did important work on developing steam engines.

The power of steam drove the Industrial Revolution of the 18th and 19th centuries, making mining, manufacturing, travel and transport very much more effective. For example, water was pumped from mines more efficiently, so mines could be dug deeper; long-distance travel and transport by rail and water improved markedly, and mass production of goods in factories concentrated employment in cities.

Demand for fuels for the energy needs of steam engines rose sharply. Employment patterns changed as new jobs were created, replacing traditional forms of work, particularly in the field of transportation. Steam continues to be used today for electricity production and manufacturing.

Many of the models and theories of thermodynamics, such as the three laws of thermodynamics, were also developed in parallel with the steam engine. This is an example of the interplay between theory, experiment and technology. Advances in any one of these usually leads to advances in the other two.

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FIGURE 5.1.1 George Stephenson (1781–1848) built one of the first efficient steam engines – 'Stephenson's Rocket' – in 1829. The steam engine is used in this chapter to explore the concept of work.

INQUIRING FURTHER

Investigate other instances where industry has driven the development of scientific theories and knowledge.

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FIGURE 5.1.2 Coal heats the boiler to produce the steam that drives the train engine's pistons.

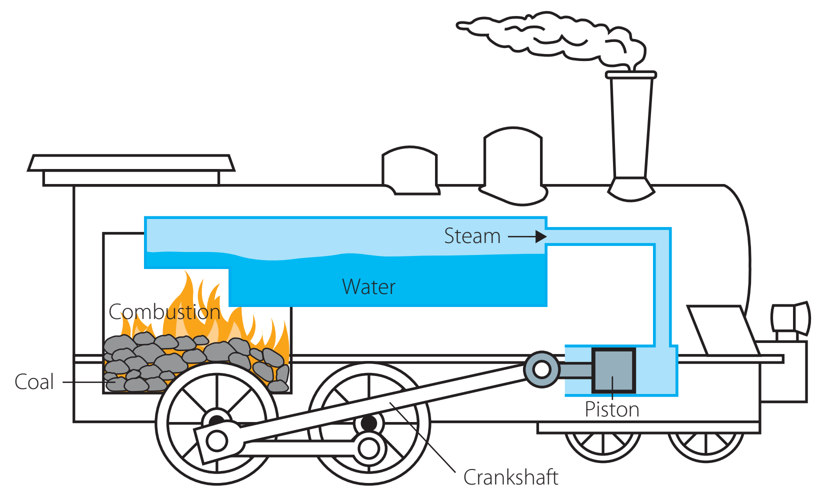
Useful systems

Consider the steam engine of a train as an example of a useful system. Steam engines are **external combustion engines**. Coal or wood or some other fuel is burnt (combusted) outside the engine and the engine does work and makes the train move. If we define our system as the engine, then the engine is not an isolated system – energy both enters and leaves the system. However, since mass is not entering or leaving the system, it can be considered a closed system.

Energy enters the system as heat, *Q*, due to the temperature difference between the combustion chamber (fire box) and the boiler in the engine. This increases the energy of the system.

external combustion engine a device to produce work through the expansion of a fluid that is heated by the combustion of an external fuel source

FIGURE 5.1.3 A diagrammatic representation of an external combustion steam engine



This heat is then used to boil water in the boiler, which creates steam. The steam is hot and at high pressure. It pushes on pistons that, in turn, push on the wheels, which push on the ground and make the engine move, pulling the carriages behind it. Hence energy is leaving the system through work since a force is being applied over some distance.

SECTION REVIEW 5.1

REMEMBERING

1 Recall the ways in which energy can be lost from a thermodynamic system.

2 Define 'work' as it relates to a thermodynamic system.

3 Define 'power' as it relates to a thermodynamic system.

UNDERSTANDING

4 Use the equations for work and power to show that the units of power could be given as $N.m\ s^{-1}$.

5 Explain how the heat from a combustion chamber in a steam engine can be used to do work on its carriages.

APPLYING

6 Calculate the power rating of an engine that does 3.0 kJ of work in 15 s.

7 If a system has a power rating of 5.0×10^3 W, how much work can it do in 2.5 minutes?

8 If a 1500 W engine pulls a carriage with a 120 N force over 225 m, for how long was the engine working?

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5.2 Change in internal energy

The total sum of all the kinetic and potential energies in a substance is defined as the *internal energy* of that substance. This can be expanded to an entire system made up of different parts to say that the total internal energy of a system is equal to the sum of its total kinetic and potential energy.

If a system loses heat to its surroundings, the internal energy of that system must decrease, and if heat is added to a system, its internal energy must increase. Similarly, since work is also a transfer of energy, it is reasonable to assume that if work is done by a system on its surroundings, the internal energy of the system will decrease, and if work is done on a system, the internal energy of the system will increase.

SYLLABUS LINK

Chapter 1 discusses internal energy.

This work–energy principle can be stated as 'the change in internal energy of a closed system, ΔU, is equal to the energy added to the system in the form of heat minus the work done by the system on its surroundings'.

KEY FORMULA

The work–energy principle

$\Delta U = Q - W$

Where:

ΔU = change in internal energy of a closed system

Q = heat added to the system from its surroundings

W = work done by the system on its surroundings

The work–energy principle is a mathematical representation of the first law of thermodynamics and its validity has never been called into question through any experimental observation. It is one of the great laws of physics and, as it shows that as energy is transferred out of a system in the form of heat or work then the internal of energy of the system must accordingly decrease, it is effectively a formulation of the conservation of energy.

When the work–energy principle is applied, it is important to be careful and to consistently follow the sign conventions for Q and W. If heat is added to the system, Q will be positive; if heat is removed from the system, Q will be negative. If work is done *by* the system on its surroundings, W will be positive and U will decrease; if work is done *on* a system, W will be negative and U will increase.

Closed systems

When the energy enters the system in the form of heat from the combustion chamber that boils the water, the internal energy of the system will increase by an amount:

$$\Delta U = +Q_{in}$$

When the steam does work to push the pistons into motion and ultimately the wheels, engine and carriages as well, the system is doing work. Energy is being transferred out of the system and therefore the change in internal energy can be represented by:

$$\Delta U = -{}^{+}W$$

The positive sign W, which is negated by the minus sign in the equation, indicates that energy is lost from the system. If no energy is lost as heat, then the total energy change is:

$$\Delta U = Q_{in} - W$$

In an ideal engine with 100% efficiency, the work done would equal the heat input. However, there is no such thing as an ideal engine. There is always some heat lost from the system to the environment, $-Q_{out}$. Hence we can write our energy equation for any real engine as:

$$\Delta U = Q_{in} - Q_{out} - W = Q - W$$

This tells us that the change in energy of the system is equal to the net heat added to the system minus the work done by the system. If the net heat in, $Q\ (= Q_{in} - Q_{out})$, and the work done (W) are equal, then the total change in internal energy will be zero. This is the case for an engine working at constant temperature; in other words, once it has reached its stable operating temperature.

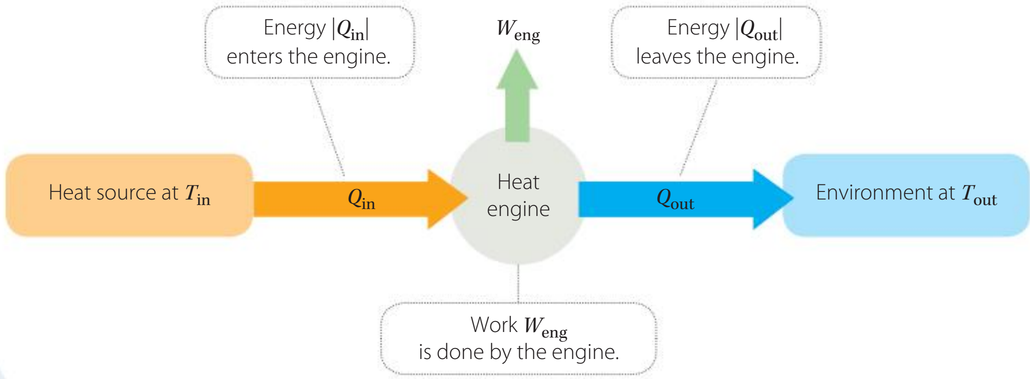

FIGURE 5.2.1 A schematic representation of a heat engine

Figure 5.2.1 shows these energy transfers. The heat source (the fire box) supplies heat to boil the water to make steam. Heat energy Q_{in} moves from here into the engine. Work is done by the engine; this is energy leaving the system. Heat is also lost by the system to its surroundings; this is Q_{out}. We call a system that converts heat into work a **heat engine**. Steam engines and petrol and diesel car engines, as well as the petrol engines that power generators and pumps, are all examples of heat engines.

heat engine
a system that converts heat energy to work

Now let us consider another system – one of the carriages. The carriage, to a first approximation, is not gaining or losing heat. However, if it is being pulled by the engine then a force is applied to it and work is done on it. In this case the change in energy is positive, energy is coming into the system, hence the sign of the work is negative (which is made positive by the minus in the equation):

$$\Delta U = -{}^{-}W = +W$$

In general, any energy change, whether it is heat or work, is positive for energy coming into a system and negative for energy leaving the system.

It is important to carefully define our system boundaries so that we know which sign to use. If we define our system as the universe, which is an isolated system, then the total energy change must always be zero. The heat going into our steam engine must have come from somewhere. It came from the internal energy of the fuel that was burned. This loss of internal energy to the environment outside the engine is equal to the gain in heat inside the engine. The total energy of the universe is conserved.

WORKED EXAMPLE 5.2.1

If 2500 J of heat is added to a system and 1800 J of work is done on the system, what is the total change in internal energy of the system?

ANSWER

Apply the work–energy principle:

$\Delta U = Q - W$

Insert known values; Q is positive since it is added to the system and W is negative because work is done on the system:

$\Delta U = 2500\text{ J} - (-1800\text{ J})$

Both are now positive, indicating that they are both processes that result in an increase in internal energy:

$\Delta U = 2500\text{ J} + 1800\text{ J}$

Calculate the answer with correct number of significant figures:

$\Delta U = 4300\text{ J}$

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WORKED EXAMPLE 5.2.2

When 250 kJ of heat is added to a steam energy that has reached its stable operating temperature, 180 kJ of work is done by the engine. Calculate the amount of heat lost by the system to its surroundings.

ANSWER

Apply the work–energy principle:

$$\Delta U = Q - W$$

$\Delta U = 0$ since the engine is at its stable operating temperature:

$$0 = Q - W$$

Q (net heat) is equal to $Q_{in} - Q_{out}$:

$$0 = (Q_{in} - Q_{out}) - W$$

Rearrange for the unknown:

$$Q_{out} = Q_{in} - W$$

Substitute the known values:

$$Q_{out} = 250\,000\text{ J} - 180\,000\text{ J}$$

Calculate the answer:

$$Q_{out} = 70\,000\text{ J}$$

Use the correct units and number of significant figures:

$$Q_{out} = 7.0 \times 10^4\text{ J}$$

SECTION REVIEW 5.2

REMEMBERING

1 Define the work–energy principle.

2 Define the purpose of a heat engine.

3 Identify the stable operating temperature of a heat engine.

UNDERSTANDING

4 If heat is added to a system, what sign will Q in the work–energy principle have?

5 If heat is removed from a system, what sign will Q in the work–energy principle have?

6 If work is done on a system, what sign will W in the work–energy principle have?

7 If work is done by a system, what sign will W in the work–energy principle have?

APPLYING

8 If 2.5 kJ of heat energy is added to a system and, in turn, it does 1200 J of work, calculate the change in internal energy of the system.

9 The combustion chamber of a steam engine delivers 5.0 kJ of heat to the boiler and the expanding steam does 3.0 kJ of work on the piston. If 1.5 kJ of heat is lost as waste, calculate the change in internal energy of the system.

10 If a heat engine at its stable operating temperature does 323 kJ of work when 440 kJ of heat is added to the system, calculate the amount of heat lost to the external surroundings.

5.3 Heat loss and usable energy

usable energy energy that can be used to perform some desired result; usually in the form of energy to do work

You only have to rub your hands together to realise that it is relatively easy to produce thermal energy by doing work. The reverse process, that of producing **usable energy** in the form of work, is much more difficult. This is the primary role of the heat engine and the first practical device that achieved this was the steam engine, which was not developed until the 18th century.

The basic idea behind any heat engine is that mechanical work can be extracted from a process in which thermal energy is transferred from an area of high temperature to one of low temperature (Figure 5.2.1, page 94).

This temperature difference is a necessary component of any heat engine. For example, consider what would happen if the region of low temperature, the boiler, were at the same temperature as the combustion engine. In this case, no heat would flow and the water in the boiler would not produce steam to push the pistons and no work would be done.

INQUIRING FURTHER

The most efficient design for an engine ever created was the Carnot engine. Although it was never developed or produced, the French scientist Sadi Carnot (1796–1832) used it to investigate ideal engines and it played an important part in the development of the field of thermodynamics. Investigate the features and efficiency of the Carnot engine.

There are many different types of engines, but they all work by converting heat from some fuel source into useful work. All real engines will also lose energy in the form of heat to their surroundings. This may be due to the presence of mechanical friction of the moving parts of the engine, turbulence of the expanding gases or other factors. Heat lost in this way reduces the overall usable energy available to the engine.

Heat exchange and conversion systems

heat-exchange system any system that transfers heat from a warmer to a cooler place

heat-conversion system a system that transforms the internal energy of a system

A **heat-exchange system** transfers heat from a warmer to a cooler location. For example, numerous capillaries in the human nasal passages maintain a temperature below core temperature. This means that air leaving the nose is cooled and air entering the nose is warmed.

A **heat-conversion system** transforms the internal energy of a system. For example, air expelled from a person's wide-open mouth feels warm, but air blown through a smaller hole feels cooler. The decrease in hole size increases pressure in the mouth. When the air is released through a small hole, it undergoes cooling as it expands rapidly, does work on the surrounding air, transfers its energy and cools rapidly. Try it yourself.

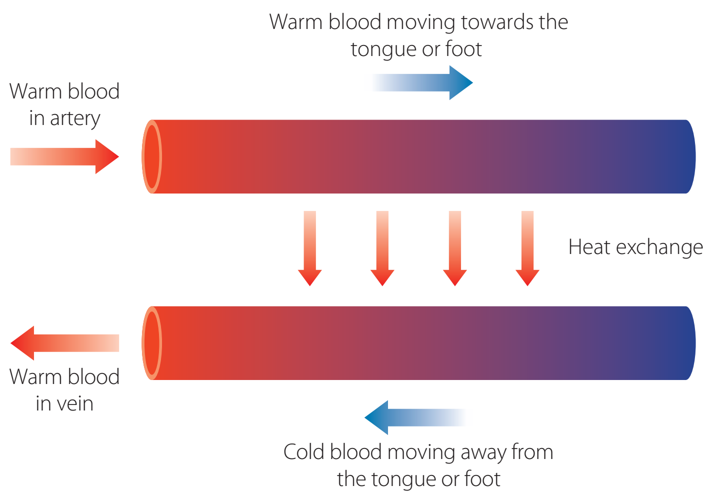

FIGURE 5.3.1 Countercurrent heat exchange between blood vessels reduces heat loss in some animals.

Heat exchange and evaporative cooling are common in nature and are used to regulate body temperature. Many modern-day cooling and heating systems use heat exchange, state change, energy release and capture, and energy conversion systems. These processes can control temperature and do useful work.

Countercurrent heat exchange

'Countercurrent' heat exchange occurs naturally in the circulation systems of fish, whales and other marine mammals. Arteries carrying warm blood from the heart to the skin are intertwined with veins carrying cool blood from the skin to the heart. This allows the warm arterial blood to exchange heat with the cooler blood in the veins. This reduces the overall heat loss in cold waters.

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Reverse-cycle heating and cooling

During winter, a reverse-cycle air conditioner extracts heat from the outside air, even on very cold nights. The evaporator coil inside the air conditioner is maintained at a much colder temperature than outside. Energy is transferred from the warmer, though very cold, outside air to the colder evaporator coil. This energy is then transferred into the house. In summer, by clever design, this cycle can be reversed and heat is extracted from the house and transferred outside. These systems are fully contained and are relatively cost efficient.

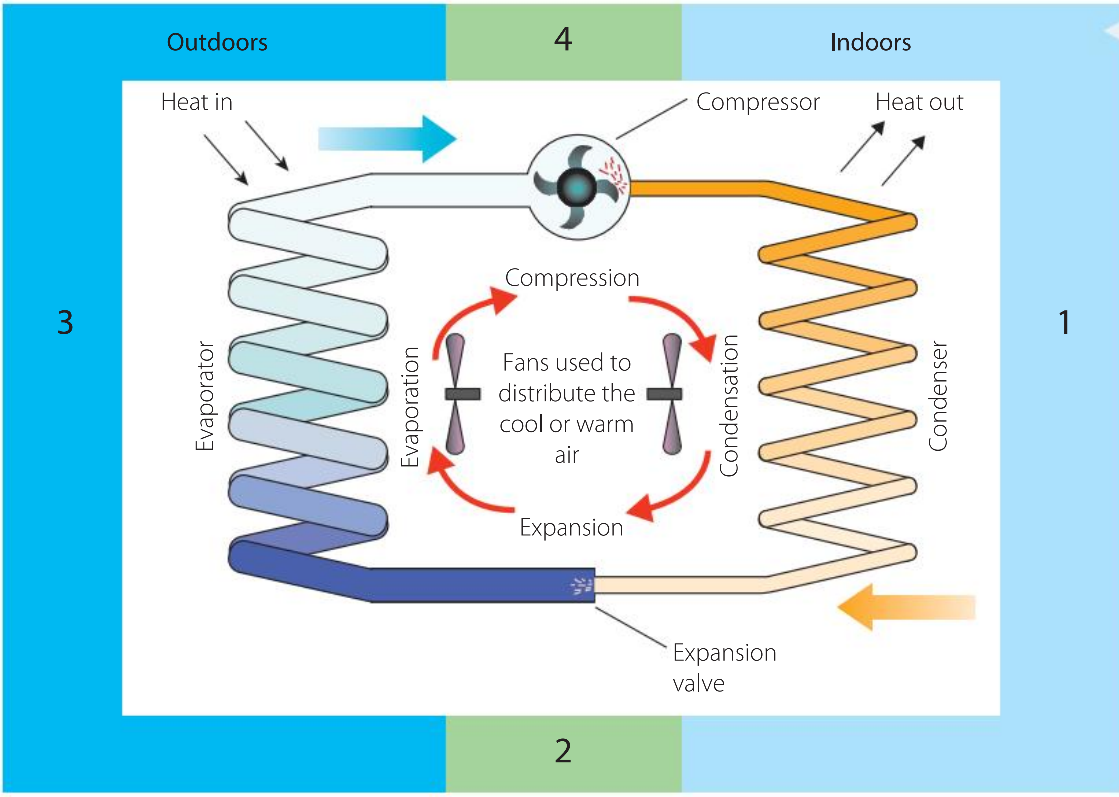

FIGURE 5.3.2 The heating cycle of a reverse-cycle air conditioner. This schematic diagram shows the energy transfers from the outdoor set of coils to the indoor set of coils by a repeating cycle of compression and expansion of a refrigerant.

As the cold gas refrigerant is passed through an external copper coil (the evaporator) between (2) and (4) in Figure 5.3.2, it absorbs heat by collision from the cool outside air particles. The refrigerant gas is then pumped through a compressor (4) where it is compressed and turns from a cool gas into a hot liquid. The compressor has transferred energy to the particles of the refrigerant by forcing them closer together. This increases the internal energy of the compressed refrigerant in the pump. Its temperature increases.

The hot liquid passes into a copper coil with a large surface area, the **condenser** (1). The hot liquid in the condenser radiates heat energy into the room. The cooler refrigerant liquid continues to pass along the condenser's copper coil until it reaches a constriction, called an expansion valve, at (2). As the refrigerant passes through the constriction it expands rapidly into the evaporator. This expansion means that the internal energy is re-balanced so that potential energy increases while the kinetic energy, hence temperature, decreases.

condenser
a vessel that removes heat from steam by allowing it to turn back to water

The expansion of the vapour in the expansion coil causes rapid cooling of the refrigerant. The cold expansion coil again absorbs heat energy from the outside, warming the coil and refrigerant. The refrigerant is then pumped back into the condenser, starting another heat-exchange cycle. The cycle will continue as long as the compressor continues to operate.

Figure 5.3.3 shows the energy transfers that occur in this system. Heat Q_{in} enters the system and heat Q_{out} leaves the system. Work, W, is done *on* the system.

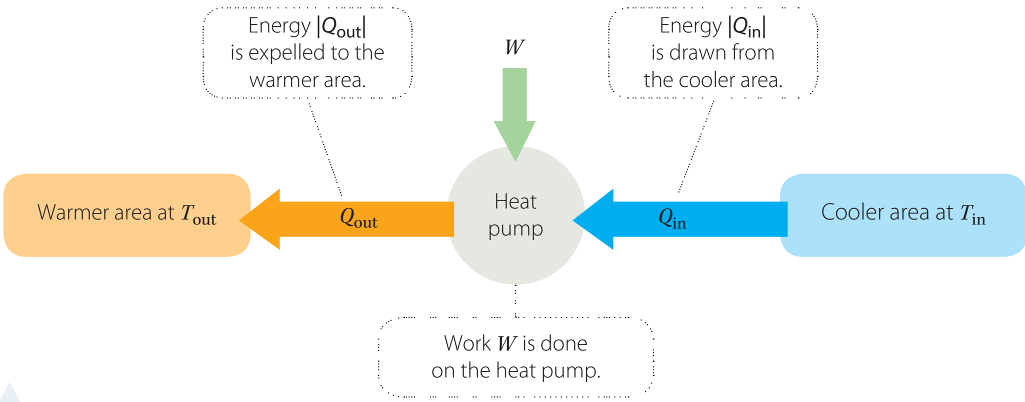

FIGURE 5.3.3 This schematic representation of a heat pump indicates the heat and work transfers taking place.

heat pump
system that moves thermal energy from one place to another

superheated steam
steam that is held under high pressure and heated to a temperature above the boiling point of water

The net effect is that heat is moved from a cooler area to a warmer area. This is impossible without some energy being used to accomplish it. This energy is supplied by the compressor. Work is done on the system by the compressor. This work is used to move the heat energy from the cooler area to the warmer area. The energy supplied to the compressor for a refrigerator or reverse-cycle heater is usually the electric potential energy that powers the motor.

This sort of system is called a **heat pump**, because it moves energy (heat) from one place to another.

The refrigerator as a heat pump

A refrigerator is a heat pump that cools the inside volume, including the food and containers. Work must be done to remove heat from inside the refrigerator. The work is done by an electric motor that compresses the refrigerant gas that passes through external coils. This causes the temperature in the coils to rise so that they radiate energy away into the cooler room (Figure 5.3.4). The gas next passes through an expansion valve into coils in the refrigerator, where it becomes cooler than the materials inside the refrigerator. Heat is transferred to the refrigerant, which cycles back via compression to the outside, and so on. The temperature is kept at an appropriate level by a sensor circuit.

Reverse-cycle heat pumps can act in the same way as refrigerators: they cool the room in summer and send the heat outside, or heat the room in winter by cooling the air outside. Coolers that use this process often drip water because the expansion coil gets very cold, causing water vapour in the surrounding air to condense.

FIGURE 5.3.4 The back of a household refrigerator. The air surrounding the coils is the heat source.

The external combustion engine

An external steam combustion engine is a heat engine that uses **superheated steam** under pressure as the working fluid to drive a piston. The water is heated outside the piston cylinder to temperatures well above boiling point. The rapidly expanding high-pressure steam transfers energy to the piston to move it. The steam is then expelled from the cylinder, where it is condensed, reheated back into steam and recycled.

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Figure 5.3.5 shows how an early James Watt external condenser steam engine worked. Taps B and C are closed and steam is introduced into the cylinder through tap A, which is open. This pushes the piston up the cylinder. Then tap A is closed and tap C is opened, allowing steam to escape under pressure into the condenser. This reduces the pressure under the piston, and air pressure and gravitational force cause the piston to fall. This expels all the steam into a separate, external cylinder. Cold water is then added into this steam through tap B to condense it.

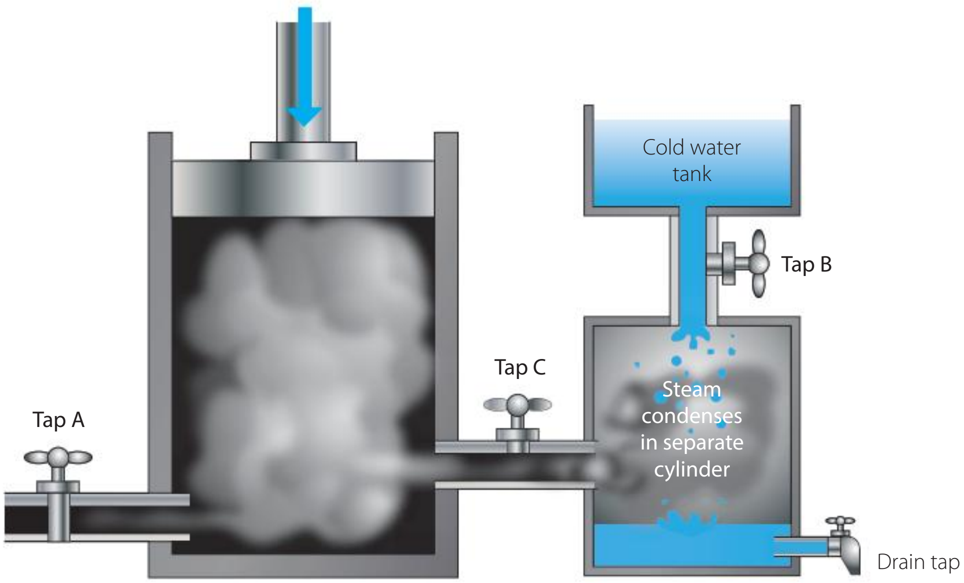


FIGURE 5.3.5 James Watt's external combustion engine with an external condenser

The piston's cylinder was always hot under these conditions, so fuel was not required to heat it again before steam was reintroduced. This also meant that the steam could be allowed to expand into the cylinder to do work, rather than continuously feeding in steam. This was a saving on the volume of steam needed and, hence, the amount of fuel used. This early design has been developed into the highly efficient engines that are used today, mainly in the generation of electrical energy.

5.3.1 Steam engine

5.3.2 James Watt

The internal combustion engine

Almost all cars currently use what is called a four-stroke combustion cycle to convert the chemical energy in the petrol into motion. The four-stroke engine was invented in 1867 by Nikolaus Otto (1832–91) . The four strokes are the intake stroke, the compression stroke, the combustion stroke and the exhaust stroke (Figure 5.3.6, page 100). High-energy fuels, such as petrol, contain large amounts of chemical energy. When they combust with oxygen, they release this energy mainly in the form of heat. When small amounts of petrol are ignited with oxygen in a confined space, large amounts of energy are released by the hot expanding gases. These expanding gases can do work if they are produced in the cylinders of a piston-driven engine.

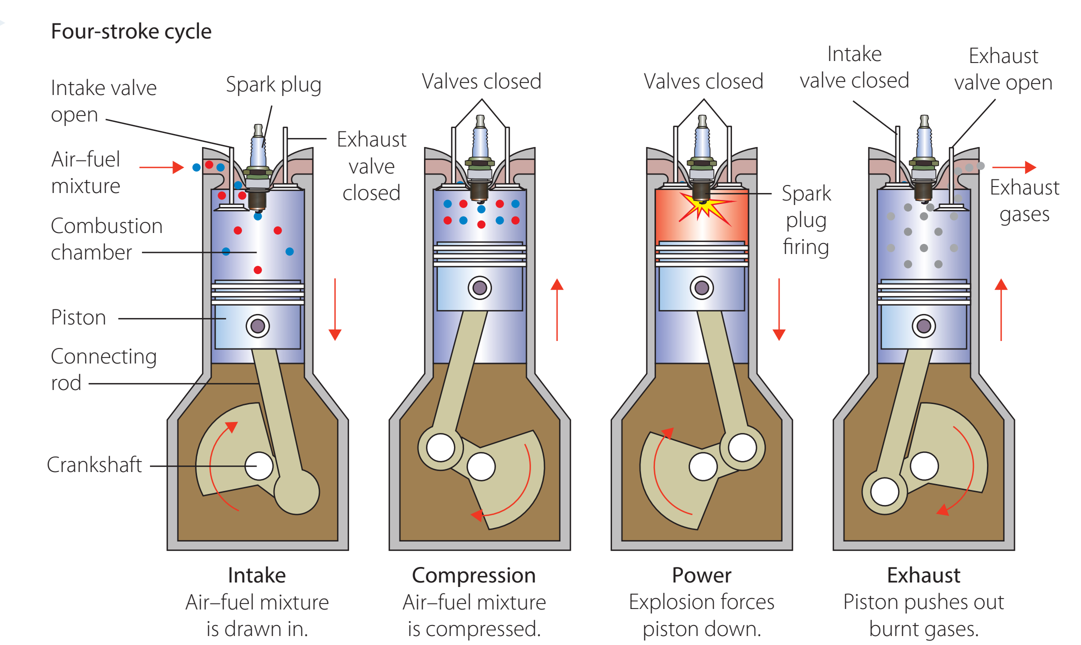
The piston is connected to the crankshaft by a rod. As the crankshaft revolves, it uses lifters to open and close the valves at the correct time during each cycle. The engine can complete the cycle thousands of times per minute.

5.3.3 Animated engines – four-stroke

5.3.4 Four-stroke engine cycle

Let us follow the four strokes of the engine cycle. We shall start with the piston at the top. The intake valve opens and the petrol–air mixture is drawn in as the piston moves down. The second step begins as the piston moves up, compressing the mixture. When the piston reaches the top, the third stage begins. In this stage the compressed mixture is ignited by the sparkplug or electronic ignition system, causing a powerful explosion that pushes the piston down. This is known as the power stroke. Once the piston reaches the bottom of its stroke, the exhaust valve opens. The exhaust gases are then expelled into the exhaust pipe as the piston moves up. This completes the cycle.

FIGURE 5.3.6 The four-stroke cycle internal combustion engine



SECTION REVIEW 5.3

REMEMBERING

1. Define 'usable energy'.
2. Describe a heat-exchange system.
3. Describe how a heat-exchange system is different from a heat conversion system.
4. Describe the difference between an internal combustion engine and an external combustion engine.

UNDERSTANDING

5. Explain why opening a refrigerator door will not cool the room it is in.
6. Use diagrams to explain how a four-stroke engine works.

5.4 Efficiency

energy efficiency the fraction of input energy that is converted in a thermodynamic process to useful output energy

The **energy efficiency**, η, of any system is the fraction of the input energy that produces a useful output. It is usually represented as a percentage.

KEY FORMULA

Efficiency of a system

$$\eta = \frac{\text{energy output}}{\text{energy input}} \times \frac{100\%}{1}$$

Where:

η = energy efficiency

WORKED EXAMPLE 5.4.1

If a system produces 3.3 kJ of usable energy output when 5.8 kJ of energy is put into it, calculate the efficiency of the system.

ANSWER

Use equation for efficiency of a system:

$$\eta = \frac{\text{energy output}}{\text{energy input}} \times \frac{100\%}{1}$$

Insert known values:

$$\eta = \frac{3.3 \text{ kJ}}{5.8 \text{ kJ}} \times \frac{100\%}{1}$$

Calculate the answer:

$\eta = 56.897\%$

Use the correct number of significant figures:

$\eta = 57\%$

The system has an efficiency of 57%.

WORKED EXAMPLE 5.4.2

If a car with an efficiency of 22% produces a usable output energy of 28 kJ, calculate the amount of chemical energy that must have been input into the engine from the fuel.

ANSWER

Use efficiency equation:

$$\eta = \frac{\text{energy output}}{\text{energy input}} \times \frac{100\%}{1}$$

Rearrange for the unknown:

$$\text{Energy input} = \frac{\text{energy output}}{\eta} \times \frac{100\%}{1}$$

Insert known values:

$$\text{Energy input} = \frac{28\,000 \text{ J}}{22\%} \times \frac{100\%}{1}$$

Calculate the answer:

Energy input = 127 272.727 J

Use correct number of significant figures:

Energy input = 130 kJ

In the case of heat engines, the input energy is equal to the heat input, Q_{in}, and the output energy is equal to the work (W) done by the system. As a result, efficiency can be rewritten as:

KEY FORMULA

The efficiency of a heat engine

$$\eta = \frac{W}{Q_{in}} \times \frac{100\%}{1}$$

If the heat engine is at its operating temperature, $\Delta U = 0$ and $W = Q_{in} - Q_{out}$, so efficiency can then be written as:

KEY FORMULA

The efficiency of a heat engine at its operating temperature

$$\eta = \frac{Q_{in} - Q_{out}}{Q_{in}} \times \frac{100\%}{1} = \left(1 - \frac{Q_{out}}{Q_{in}}\right) \times \frac{100\%}{1}$$

WORKED EXAMPLE 5.4.3

A steam engine working at its operating temperature uses 5.6 kJ of heat energy every second and has an efficiency of 27%.

a Calculate the amount of usable mechanical energy that will be produced every second.

b Determine the amount of waste heat that is radiated from the engine every second.

ANSWERS

a Use the heat engine equation:

$$\eta = \frac{W}{Q_{in}} \times \frac{100\%}{1}$$

Rearrange for the unknown value:

$$W = \frac{\eta \times Q_{in}}{100\%}$$

Insert known values:

$$W = \frac{27\% \times 5600 \text{ J}}{100\%}$$

Calculate the answer:

$W = 1512$ J

Use the correct number of significant figures:

$W = 1.5$ kJ

b Use the operating temperature equation:

$$\eta = \left(1 - \frac{Q_{out}}{Q_{in}}\right) \times \frac{100\%}{1}$$

Rearrange for the unknown value (this exercise is left to you):

$$Q_{out} = Q_{in}\left(1 - \frac{\eta}{100\%}\right)$$

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Insert known values:

$$Q_{out} = 5.6\left(1 - \frac{27\%}{100\%}\right)$$

Calculate the answer:

$Q_{out} = 4.088 \text{ kJ}$

Use the correct number of significant figures:

$Q_{out} = 4.1 \text{ kJ}$

Note: As the problem involves a heat engine working at its operating temperature, part b could have been solved by realising that:

$Q_{out} = Q_{in} - W$

SCIENCE AS A HUMAN ENDEAVOUR

A car is, at best, about 30% efficient because only 30% of the chemical energy released by combustion of the fuel is used for moving the car. The other 70% of the energy is transferred to the environment, mostly in the form of heat and sound.

High-grade energy resources, such as solar, chemical and electrical energy, transform energy relatively efficiently. Low-grade energy resources, principally heat, transform energy inefficiently. When producing a desired output, all open systems transform energy from high-grade resources to low-grade resources.

Improving the efficiency of the way we produce, transfer and utilise energy is becoming increasingly important. At present our greatest source of useable energy comes from the burning of fossil fuels, which are a non-renewable resource. In addition, fossil fuels are a major source of greenhouse gases. These gases contribute to the warming effect of the atmosphere. Decreasing greenhouse emissions by developing and using more efficient technologies will reduce the anthropogenic effects on the climate.

Use the concepts of energy transfers and efficiency to consider the economic and ethical implications inherent in the choice to use more efficient technologies.

SECTION REVIEW 5.4

REMEMBERING

1 Define 'efficiency'.

APPLYING

2 An engine has an energy output of 35 kJ when 105 kJ of energy is input into the system.

- **a** Calculate the efficiency of the engine.
- **b** What happened to the remaining 70 kJ of energy?

3 If 900 J of energy is input into a system with an efficiency of 25%, calculate its energy output.

4 If a car can do 350 kJ of work when 1700 kJ of heat is added to it, calculate its efficiency.

5 A heat engine that is 19% efficient at its stable operating temperature releases 115 kJ of energy to the surroundings.

- **a** Calculate the energy that must have been input into the system.
- **b** Calculate the amount of work done by the system.

CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 Define the following terms.

- a Work
- b Heat
- c Internal energy
- d Usable energy
- e Heat-exchange system
- f Heat-conversion system
- g Heat pump
- h Heat engine
- i External combustion engine
- j Energy efficiency

CATEGORY QUESTIONS

2 Explain the work–energy principle in terms of internal energy, work and heat.

3 Give two examples of how the internal energy of a system could be made to increase by the action of heat or work.

4 Give two examples of how the internal energy of a system could be made to decrease by the action of heat or work.

5 Explain how the steam engine converts heat to work.

6 Give three examples of a heat-conversion system.

ELABORATION QUESTIONS

7 Using the kinetic particle model, explain what happens to a system if a thermodynamic process results in a loss of heat from the system or an amount of work being done by the system.

8 Explain why no heat-conversion system can ever be 100% efficient.

9 Did the Industrial Revolution drive the advancement of science and technology or did the advancement of science and technology drive the Industrial Revolution?

10 Given that any heat conversion results in an overall loss of usable energy to the system through heat loss, explain any consequences our current fossil fuel demands may have for the future.

EVIDENCE QUESTIONS

11 Find evidence that the same mutually beneficial relationship between science and industry still exists today as there was at the time of the Industrial Revolution.

12 If the system from Question **10** was extended to include the entire universe, would the same consequences still apply?

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END-OF-CHAPTER EXAM

End-of-chapter test

PHYSICS

1 Which of the following results in a decrease in the internal energy of a system?

A Heat is added to the system.

B Work is done on the system.

C Work is done by the system.

D Kinetic energy is added to the system.

2 Which of the following is not a unit for work?

A Watt

B Joule

C Newton metre

D $\text{kg m}^2\text{ s}^{-2}$

3 An increase in which of the following terms would result in an increase in the efficiency of a heat engine?

A Q_{in}

B Q_{out}

C U

D W

4 What is the value of the change in internal energy when an external combustion engine is working at its stable operating temperature?

A W

B 0

C Q_{in}

D Q_{out}

5 Is the steam engine an open, closed or isolated system?

6 What name is given to the ratio of output energy to input energy?

7 Define 'power'.

8 Explain the work–energy principle.

9 Define 'usable energy'.

10 If 1800 J of energy is removed from a system in the form of heat when 2500 J of work is done on the system, calculate the overall change in internal energy of the system.

11 Calculate the efficiency of an engine that performs 1.6 kJ of work for every 8.5 kJ of heat that is added.

12 Use the example of the steam engine to explain how an external combustion engine can be used to do useful work. Include a diagram in your answer.

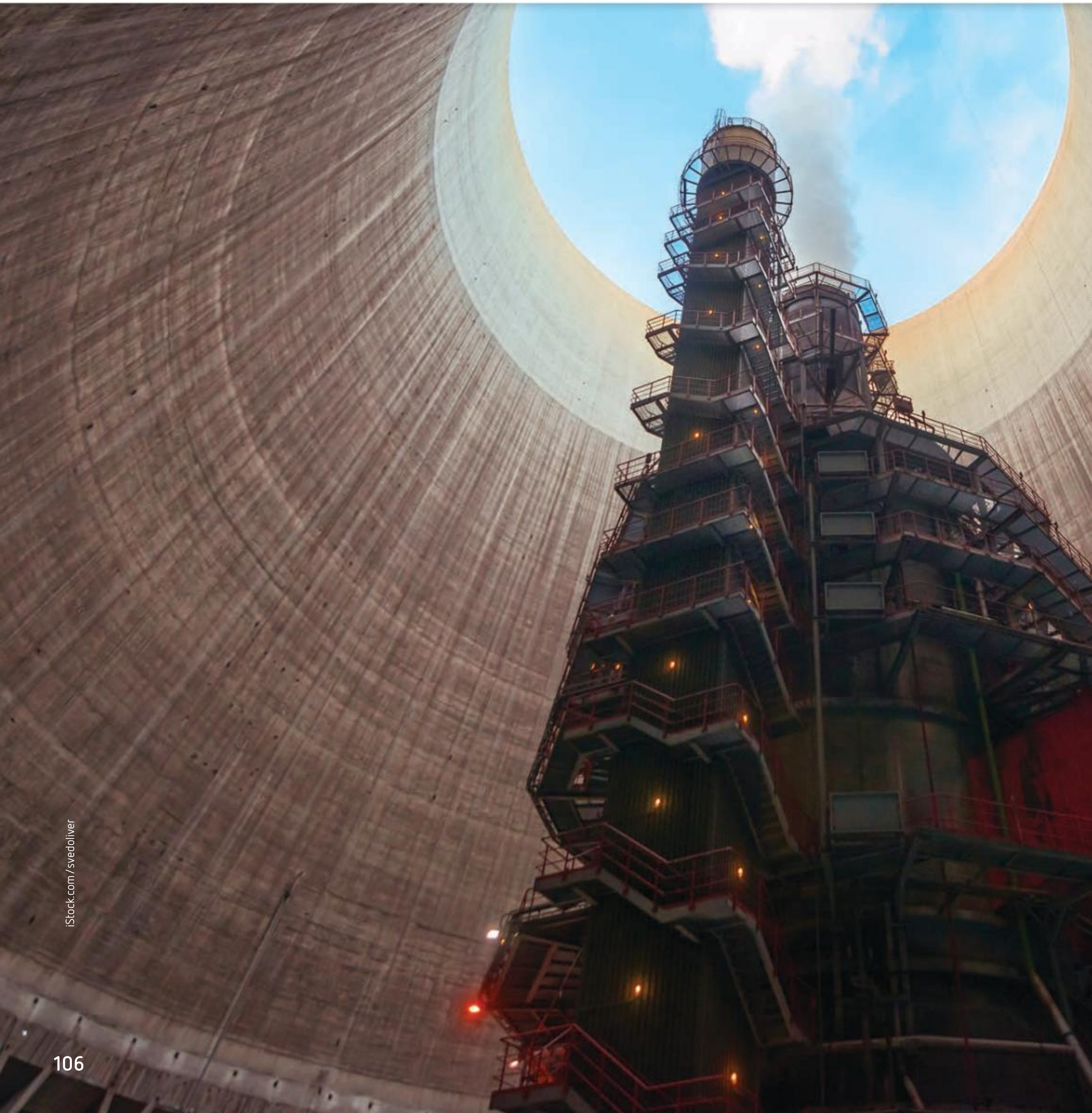
13 When a heat engine is working at its stable operating temperature it releases 1.2 kJ of waste heat for every 5.0 kJ of input heat. Calculate the amount of work performed by this engine.

14 A heat engine of 15% efficiency working at its stable operating temperature has a power output rating of 12 000 W.

a Calculate the amount of heat input that is required by this engine every minute.

b Calculate the amount of heat that is radiated every second.

THERMAL, NUCLEAR AND ELECTRICAL PHYSICS



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Topic 2: Ionising radiation and nuclear reactions

The topic 'Ionising radiation and nuclear reactions' introduces students to the nuclear model and phenomena related to spontaneous decay, including the strong and weak nuclear force, half-life equations, and energy and mass defect. Alpha, beta and gamma radiation are explored, including balanced nuclear equations, determining half-lives and solving problems involving Einstein's mass–energy equivalence relationship for nuclear binding energy, and nuclear fission and fusion. Practical skills in performing research into nuclear safety, and evaluating sources of information in terms of bias, relevance and accuracy are also addressed.

SCIENCE AS HUMAN ENDEAVOUR

Students should be given opportunities to investigate: how radiometric dating has made a contribution to historical understanding; understanding the risks and benefits of nuclear energy; nuclear fusion in stars

KEY FORMULA

$$N = N_o\left(\frac{1}{2}\right)^n$$

$$\Delta E = \Delta mc^2$$

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6 NUCLEAR MODEL AND STABILITY

Introduction

All matter, living or not is composed of nothing more than millions and trillions of atoms. Different atoms have uses in different fields from construction materials, to nuclear power and radiation treatments for medical purposes. Recently, scientists have been able to photograph shadows of atoms, and surprisingly, the major constituent of these small particles, once believed to be indivisible, is just empty space.

Stimulus questions

If the universe is composed of atoms, and atoms are 99% empty space, how does everything stay together?

Does gravitational force keep protons together?

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6.1 The nuclear model

The nucleus lies at the centre of the atom and contains the subatomic particles that distinguish the elements from one another. The discoveries that led to the current understanding of the nucleus of the atom have been the life-consuming work of many scientists. After many experiments and years of development, a common understanding of the atom has come to light: there is an extremely small nucleus at the centre of an atom, and this nucleus contains the vast majority of the atom's mass.

nucleus
centre of an atom, which comprises the majority of an atom's mass

atom
particle; originally thought to be indivisible, but now known to comprise numerous smaller particles

subatomic particles
particles within an atom

The atomic model

Democritus (460 BCE–370 BCE) was the first to propose the idea of the atom as the smallest, indivisible particle of matter. At the time, this was a powerful idea, but it has never entirely been accepted. The idea of something this small and fundamental was ground-breaking and provoked many scientists to work towards developing a deeper understanding of the atom.

The plum pudding model

In 1897, JJ Thomson (1856–1940) discovered the electron by applying a high voltage across a gas at very low pressure. This discovery gave support to the idea that within an atom there were more fundamental particles. Thomson proposed a model for the atom, comprising of a uniformly positive region of charge within which negatively charged electrons were distributed. The model was dubbed the 'plum pudding' model (Figure 6.1.1), because the electrons appeared to be like raisins stuck in a plum pudding.

electron
negatively charged subatomic particle with mass 9.11×10^{-31} kg

INQUIRING FURTHER

Research the experiment that led Thomson to discover to electron. What did he measure to come to his conclusion? How was he acknowledged for his discovery?

Rutherford's model

In 1909 Ernest Rutherford (1871–1937) designed an experiment to test Thomson's plum pudding model. Famously called the gold foil experiment, Rutherford fired positively charged particles (alpha particles, which are helium nuclei) at an extremely thin piece of gold foil. If Thomson's model was correct, the particles would pass through the foil as though uninterrupted. When the experiment was carried out, it was noticed that some alpha particles were deflected slightly from a straight path, and a small number bounced almost directly backwards from the foil (1 in 20 000 reflected back straight towards the source). This revolutionary result prompted Rutherford to develop his own atomic model, refined from the plum pudding model. He suggested that rather than a uniformly positively charged region, there was a dense region of positive charge (explaining the deflection and reflection of alpha particles – termed 'scattering') and that there

alpha particle
a particle containing two neutrons and two protons; a helium nucleus

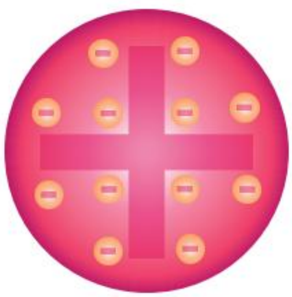

FIGURE 6.1.1 Thomson's 'plum pudding' model of the atom shows electrons in a positively charged sphere of electrification producing a neutrally charged atom overall.

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was a light, negatively charged space in which the electrons circulated. He analogised these circulating electrons to planets orbiting the Sun, in which the Sun represented a dense, positively charged nucleus.

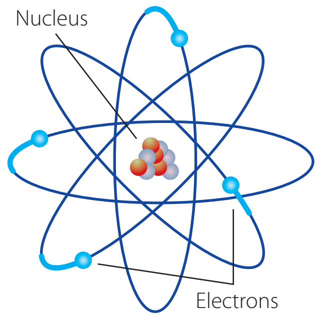

FIGURE 6.1.2 Rutherford's planetary model of the atom

Rutherford–Bohr model

Unfortunately, the idea that negatively charged electrons could orbit freely while maintaining all their energy was a serious violation of the laws of classical electrodynamics. Developed by James Clerk Maxwell (1831–79), Maxwell's equations are effective in describing, explaining and predicting a vast array of electromagnetic phenomena. For example, as a charged particle (e.g. an electron) orbits or passes other charged objects (e.g. a positively charged nucleus) it should slow down, and spiral into the centre. There was no evidence that this was happening in Rutherford's planetary model. Niels Bohr (1885–1962) worked extensively with Rutherford, and suggested that electrons could only have specific energies, and within those energy states the electrons could not radiate or lose any energy. Within this model, all laws of physics are maintained, whereby electrons occupy discrete energy levels and the nucleus is located at the centre of the atom.

6.1.1 The 2400-year-old search for the atom

The nuclear conclusion

The percentage of mass contained in the nucleus and the volume of the nucleus as a percentage of the size of the atom are summarised in Table 6.1.1.

TABLE 6.1.1 Percentage mass and volume of the nucleus of an atom

COMPONENT OF ATOM	PERCENTAGE MASS OF ATOM	PERCENTAGE VOLUME OF ATOM
Nucleus	>99%	<1%
Remainder of atom (space and electrons)	<1%	>99%

The properties of the Rutherford–Bohr model are as follows:

- The nucleus contains most of the mass.
- The nuclear charge is positive and equal in size to the total electronic charge.
- Electrons exist in orbitals that correspond to allowed energy states.
- The atom is much bigger than the nucleus.

This is our current understanding of the model of the atom.

INQUIRING FURTHER

1 Create a timeline of scientific development from 1880 to 1930 that includes the year, the name of scientist, their country of origin and their main contribution. Include a column in which to add interesting scientific or biographical information. (You could add to this timeline as you meet other scientists involved in the development of the nuclear model of the atom.)

2 Explain how the timeline demonstrates the importance of international cooperation in scientific developments during this period.

3 In his 1981 book *The Physicists*, CP Snow said that from the late 19th century to 1930 ' nearly all the scientists … tended to expect other human beings to be as free from class and racial tensions as they were themselves' (p. 76). How did this way of approaching science help to develop knowledge about the atom and radioactivity? In making your case, refer to the timeline, and to particular physicists and their work.

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PRACTICAL ACTIVITY 6.1.1

Atomic scale

The nucleus is very small and dense, and comprises a small part of the atom. This practical aims to give some idea of how much space there is between the electrons orbiting a nucleus, and the nucleus itself. The ratio of the diameter of the nucleus to the diameter of the hydrogen atom is approximately 1:100 000.

MATERIALS

- a small round object such as a pea or small ball bearing
- a trundle wheel
- a class of students

PROCEDURE

1. Measure the diameter of the pea and record it in metres.
2. Calculate the radius of an atom if it had a nucleus the size of the pea.
3. Head outside and have a group member hold the pea in the centre of a large space, such as an oval.
4. Have each student measure out the scale radius for an atom as calculated in step 2. This gives an idea of how large each atom is compared to a nucleus.

ALTERNATIVE MATERIALS

- large butcher's paper

ALTERNATIVE PROCEDURE

1. It may help to cover a large area of floor space with butcher's paper for this activity. In the centre of a large piece of butcher's paper, make a dot with the tip of your pen. This dot should be approximately 1 mm in diameter.
2. Determine the diameter of an atom if the nucleus was 1 mm in diameter. Measure this length across the dot at several points, until a circle can be sketched.
3. Sketch the circle, and note that the pencil or pen you are drawing the atom boundary with is thicker than the nucleus you drew in the centre.

SECTION REVIEW 6.1

REMEMBERING

1. List the three subatomic particles and their respective charges.
2. Name the scientists who have been integral in understanding the model of the atom.

UNDERSTANDING

3. Explain why the model of the atom keeps changing over time.

ANALYSING

4. Distinguish the key differences between Rutherford's model of the atom and the Rutherford–Bohr model. Discuss how Bohr's model was different and why it is currently accepted as the model of the atom.

6.2 Protons

proton
positively charged subatomic particle within the nucleus of an atom

neutron
a neutrally charged subatomic particle within the nucleus of an atom

nucleon
a proton or neutron; a particle that makes up the nucleus of an atom

Now that we have seen the model for the atom, we can begin to further explore the nucleus. As stated earlier, the nucleus contains most of an atom's mass, suggesting that the subatomic particles that make up the nucleus are relatively heavy compared to the electrons surrounding the nucleus. These subatomic particles are **protons** and **neutrons**. Protons and neutrons are collectively called **nucleons**.

Rutherford discovered the proton in 1919. He found that protons are positively charged, equal in charge to an electron, but approximately 1800 times more massive.

Protons are positively charged, so being too close together in a nucleus will cause them to repel each other. This called into question how atoms stayed together. In 1932, Sir James Chadwick (1891–1974) discovered the neutron. Neutrons have a slightly greater mass than a proton and carry zero charge (neutrally charged), so having neutrons between the positively charged protons helps combat this repulsive electrostatic force by increasing the distance between protons and by providing a 'gluing' force to maintain the stability of the nucleus. This will be explored later in the chapter.

Elements, isotopes and nuclides

6.2.1 Protons, neutrons and electrons

The difference between different types of atoms depends on what is in the nucleus. As electrons are in energy shells (Figure 6.2.1) that are far away from the centre of the atom, it is easy for electrons to be lost or gained depending on the atom's surroundings. This is known as ionisation. When an atom has more electrons, or fewer electrons than the number of protons, it is said to be a negatively or positively charged ion respectively. It is important to recognise that this exchange of electrons and the overall charge of an atom has nothing to do with the *nucleus*.

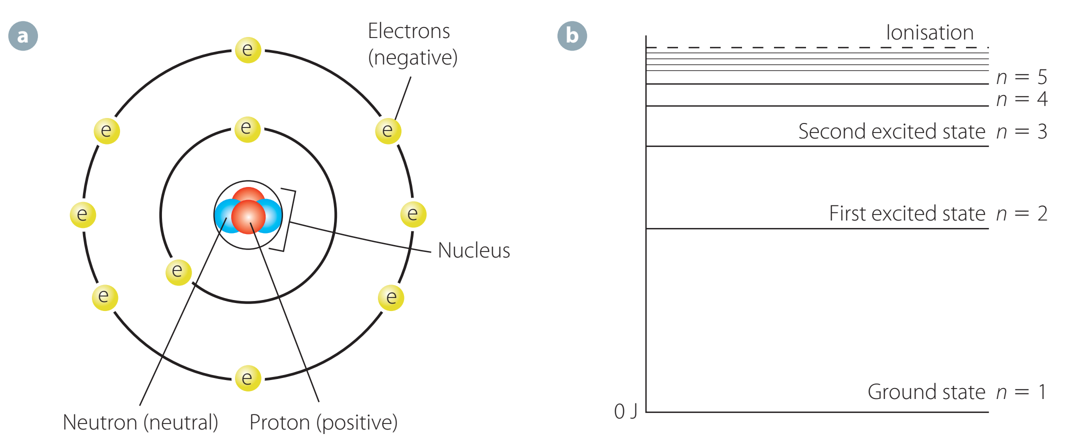

FIGURE 6.2.1 (**a**) The Rutherford–Bohr model of the atom, in which the nucleus is composed of protons and neutrons, and the outer shells contain the electrons. (**b**) Rutherford–Bohr energy level model. Each state represents how much energy an electron would need to absorb to move to a state higher than $n = 1$.

Elements

element
a substance that only has atoms with the same number of protons

The number of protons in the nucleus *defines* an **element**. Elements are not affected by the ionic charge of an atom. The periodic table arranges the known elements according to the number of protons in the nucleus. For example, hydrogen has one proton in its nucleus, and sulfur has 16.

Isotopes

isotopes
elements with the same number of protons, but a different number of neutrons in the nucleus

Although each element has a unique number of protons, there are different *versions* of these elements. An **isotope** has the same number of protons but a different number of neutrons in the nucleus. This does

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not change the element, but it changes the size of the nucleus of the element and, in turn, the mass of the element. Different isotopes of elements occur naturally and in different abundances. Some isotopes that have high numbers of neutrons or protons are unstable and these are called radioisotopes.

nuclides
elements with the same number of protons and neutrons with the nucleus in the same energy state

Nuclides

A **nuclide** is a species of atom classified according to the number of protons and neutrons *as well as* its energy state. There are different energy levels within a nucleus, and an atom is most stable when the nucleus is in its lowest energy level – its **ground energy state**. As the number of protons in a nucleus increases, more and more neutrons are required to overcome the electrostatic force. This only works until a certain point at which there are simply not enough neutrons to hold the nucleus together (an example is uranium). In these cases, a nuclide would not be in its ground state, but rather it would have a lot of energy, and would need to decay in order to be stable.

The term 'nuclide' is used to describe all possible elements and isotopes in the periodic table. 'Isotope' is used to distinguish elements with different numbers of nucleons in their nucleus, due to different numbers of neutrons, whereas the term 'element' is used when talking exclusively about proton number.

SYLLABUS LINK

Chapter 7 discusses radioisotopes, spontaneous decay and half-life.

ground energy state
the state in which a nucleus has absorbed no energy, and requires no additional energy to maintain its state

Atomic number and mass number

Nuclides are named according to the number of nucleons they have. Carbon has six protons and six neutrons; it is called carbon-12 as there are 12 nucleons. This differs for other isotopes of carbon. Carbon that has seven neutrons is called carbon-13, and if it has eight neutrons it is called carbon-14. Thus, we write different nuclides according to their **atomic number Z** and **mass number A**. The atomic number Z is the number of protons in the nucleus, and the mass number A is the number of nucleons the element has (protons + neutrons). The number of neutrons is denoted N.

atomic number (Z)
number of protons in a nucleus

atomic mass number (A)
total number of protons *and* neutrons in a nucleus

Notation

In addition to writing carbon-12 for the isotope of carbon with six protons and six neutrons, we have a universal notation for showing the atomic and mass number of the element, based on its symbol in the periodic table. Figure 6.2.2 shows the international standard notation for representing nuclides. The chemical symbol has the atomic mass (A, the nucleon number) as a left superscript, and the atomic number (Z, the number of protons) as a left subscript. Have a look at the periodic table and, from the symbols given, work out the atomic and mass numbers of iron, platinum and gold.

KEY FORMULA

$N = A - Z$

Where:

N = number of neutrons

Z = atomic number denoting the number of protons

A = mass number denoting the number of protons and neutrons within the nucleus

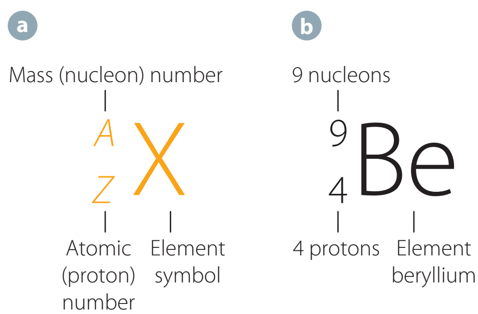

FIGURE 6.2.2 (**a**) International standard notation for representing a nuclide. (**b**) Standard notation for the element beryllium.

Nuclide families

Nuclides are sorted into families in a number of ways, further to those shown in the periodic table. They can be sorted by the number of protons (isotopes), the number of nucleons (isobars), number of neutrons (isotones) and energy states (isomers). This is summarised in Table 6.2.1 (page 114).

If a nuclide can exist in an energy state above its ground state for more than 10^{-12} s, then it is called a **metastable** nuclide.

metastable
a nuclide is metastable if it can remain in a higher energy state for a certain period of time

atomic weight (relative atomic mass)
used interchangeably with *relative atomic mass*, atomic weight is the weighted average of all the masses of the different nuclides in a pure, naturally occurring sample of the element

TABLE 6.2.1 Nuclear families

FAMILIES	NUCLIDES WITH THE SAME:
Isotopes	atomic (proton) number, Z
Isobars	mass (nucleon) number, A
Isotones	number of neutrons, $A - Z$
Isomers	Z and A, but different energy states

Atomic weight

Within a sample of an element there is normally more than one isotope of the element. The **atomic weight** (or **relative atomic mass**), is the weighted average of the masses of the different nuclides in a pure, naturally occurring sample of the element. This is scaled according to the natural abundance of each isotope. For example, the relative atomic mass of silver is 107.96. This is calculated from the knowledge that 51.84% of Ag-107 and 48.16% of Ag-109 are found in pure silver naturally. The atomic weight should not be confused with the mass number of a nuclide.

WORKED EXAMPLE 6.2.1

Pure silver contains 51.84% of isotope $^{107}_{47}\text{Ag}$ and 48.16% of $^{109}_{47}\text{Ag}$. Determine the atomic weight of silver.

ANSWER

Multiply the mass number by the percentage, and sum the two:

Weighted average $= 107 \times 0.5184 + 109 \times 0.4816$

Give the answer:

Atomic weight of silver $= 107.96$ amu

SECTION REVIEW 6.2

REMEMBERING

1 For the general nuclide $^{A}_{Z}\text{X}$, what do A, X and Z represent?

2 Define 'element', 'isotope' and 'nuclide'.

UNDERSTANDING

3 Compare and contrast atomic mass and atomic weight.

4 Does the number of electrons define an element? Explain your answer.

APPLYING

5 Find the number of neutrons in $^{136}_{57}\text{La}$.

6 Europium comes in two different isotopes, $^{153}_{63}\text{Eu}$ (52.18%) and $^{151}_{63}\text{Eu}$ (47.82%). Find the atomic weight (relative atomic mass) of europium.

ANALYSING

7 An isotope of an element is sometimes referred to as 'the element'. Highlight how this can cause confusion between these terms.

8 Molybdenum-99 is formed when a nuclide absorbs a neutron. What is that nuclide?

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6.3 Strong nuclear force

As stated earlier, protons have positive charge and positive charges repel each other. This repulsion is caused by the electrostatic force. The electrostatic force becomes relatively large when the protons are close together. In a nucleus, protons come to within 2×10^{-15} m of each other. This causes an electrostatic force of about 60 N between two protons within the nucleus. This value is calculated using **Coulomb's law**. This law states that the force between two charges is inversely proportional to the square of the distance between them.

Coulomb's law describes the force of attraction or repulsion between two charges, separated by some distance

KEY FORMULA

Coulomb's law

$$F = \frac{kqQ}{r^2}$$

Where:

F = force between the two charges q and Q in newtons (N)

k = the constant 9.0×10^9 N.m^{2}C^{-2}

q = charge in coulombs of one charge (C)

Q = charge in coulombs of the other charge (C)

r = distance that separates the charges, measured from their centres (m)

WORKED EXAMPLE 6.3.1

a If protons within a nucleus come within 2×10^{-15} m of each other, and each proton has a charge of 1.6×10^{-19} C, what is the electrostatic force of repulsion between them?

b If the distance between the protons doubled, what would happen to the electrostatic force between the protons?

ANSWERS

a Use Coulomb's law:

$$F = \frac{kqQ}{r^2}$$

Substitute the known values and calculate the answer:

$$F = \frac{9.0 \times 10^9 \times 1.6 \times 10^{-19} \times 1.6 \times 10^{-19}}{(2 \times 10^{-15})^2}$$

$$F = \frac{2.3 \times 10^{-28}}{4 \times 10^{-30}}$$

Give the answer with the right unit:

$F = 57.6$ N

b We know $F = \frac{kqQ}{r^2}$

and that the distance has doubled. So the new force will be calculated by:

$$F_2 = \frac{kqQ}{(2r)^2}$$

$$F_2 = \frac{kqQ}{4r^2}$$

$$F_2 = \frac{1}{4} \times \frac{kqQ}{r^2}$$

$$F_2 = \frac{1}{4} \times F_1$$

Therefore if the distance between protons doubles, the force will decrease by a factor of 4.

SYLLABUS LINK

Chapter 5 discusses Newton's law of universal gravitation.

Protons have mass and masses attract each other. This is called gravitational force. The gravitational force between two masses can be calculated with Newton's universal law of gravitation. For the above scenario, if two protons are 2×10^{-15} m away from each other and each has a mass of 1.67×10^{-27} kg, the gravitational force between them can be calculated as approximately 4.65×10^{-35} N of attraction. This is nowhere near enough attractive force to overcome the 60 N of electrostatic repulsion they experience! So how do protons in a nucleus stay together?

strong nuclear force
the force required to hold nucleons together, especially to overcome the electrostatic force of repulsion between protons.

Protons stay together in the nucleus due to the **strong nuclear force**. The strong nuclear force is created between nucleons by the exchange of particles called mesons. Neutrons provide the means by which protons are kept far enough apart to so that they don't repel each other, but also participate in the meson exchange, which contributes to increased strong nuclear force. The strong nuclear force is essentially independent of whether the nucleons are protons or neutrons.

The strong nuclear force overcomes the electrostatic force of repulsion, and provides the 'glue' that keeps the protons, neutrons and atoms – the building blocks of the universe – together. Over the small distances involved, the strong nuclear force is the strongest of the four fundamental forces in the universe.

SYLLABUS LINK

Chapter 13 discusses mesons.

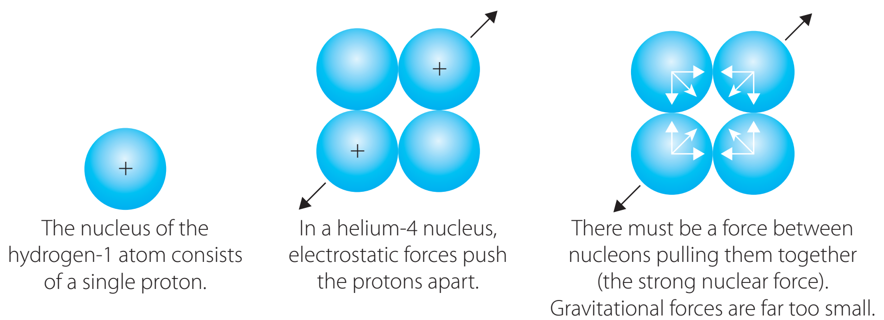

FIGURE 6.3.1 Representation of the strong nuclear force holding a nucleus together

Four fundamental forces

Physicists have identified four fundamental forces that are key to understanding the universe. At the nuclear level, the strong nuclear force has the greatest effect on keeping nucleons in the nucleus, overcoming the smaller electrostatic force. The gravitational force is a distant last in terms of strength. There is a fourth force, the weak nuclear force, which acts within nucleons. If the strength of the gravitational force is compared with the effect of the other three forces at the nuclear level, the others are far greater.

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It is important to note that the size of a charge, mass or distance between two objects will determine which force is stronger. For example, over extremely small distances such as within a nucleus, the strong nuclear force is stronger than the gravitational force between protons. In contrast, over astronomical distances the gravitational force between planets (very large masses) is much larger than the other forces.

6.3.1 Four fundamental forces

SCIENCE AS A HUMAN ENDEAVOUR

THE FIFTH FUNDAMENTAL FORCE

The idea of a fifth force of nature has recently gained a lot of traction. Recent findings have suggested that a previously unknown subatomic particle has caused an anomaly in an experiment at the Hungarian Academy of Sciences.

Research this scientific breakthrough and answer the following questions:

1 What caused scientists to think that there was an additional, unknown force at play?

2 Suggest what this new understanding would mean for scientists.

3 Propose how this could be further researched by current scientists, and what it would mean for the scientists who could confirm this theory.

TABLE 6.3.1 Comparison of the effect of the four fundamental forces within a nucleus

	GRAVITATIONAL	WEAK NUCLEAR	ELECTROMAGNETIC	STRONG NUCLEAR
Relative magnitude	1	10^{32}	10^{36}	10^{40}
Range (m)	Infinite	10^{-18} or 1 attometre, 1 am	Infinite	10^{-15} or 1 fm

SECTION REVIEW 6.3

REMEMBERING

1 List the four forces that act within the nucleus, in order of strength.

2 Recall why the strong nuclear force is considered the strongest force in the universe.

UNDERSTANDING

3 Discuss what would happen if there was no strong nuclear force.

4 If two protons are 6×10^{-15} m apart, what is the electrostatic force of repulsion between them?

ANALYSING

5 In the last part of Figure 6.3.1 there are arrows on the four nucleons, showing the direction of the strong nuclear force between them. Draw a vector diagram for one of these nucleons, showing all the forces it is experiencing. Be sure to include the gravitational, electrostatic and strong nuclear forces.

6 From the forces calculated in this chapter, and your vector diagram from Question **5**, calculate the strong nuclear force required to keep all the four nucleons together in a helium-4 nucleus.

6.4 Nuclear stability

The stability of a nucleus is determined by several different factors. These include operation of the strong nuclear force over very short distances, electrostatic repulsion, and the relative number of protons and neutrons in the nucleus.

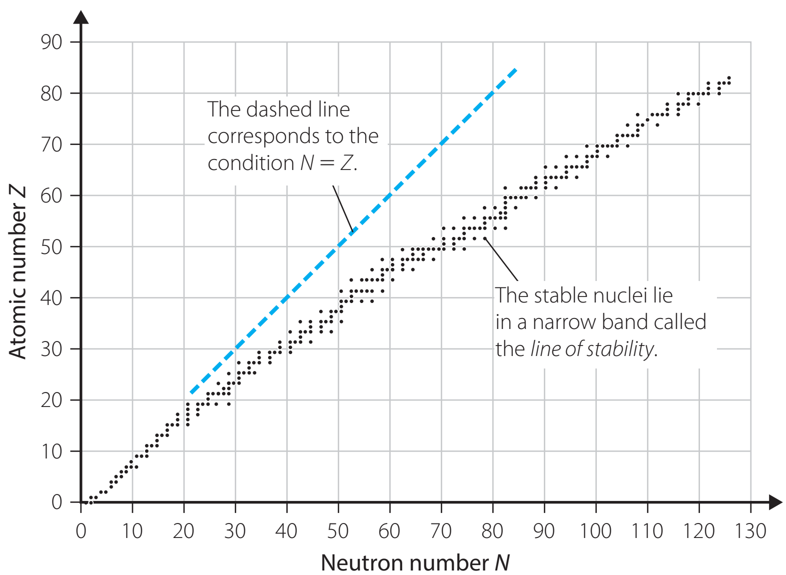
The more neutrons in the nucleus, the stronger the force that helps glue the nucleus together. As nuclei become larger, specifically as the atomic number becomes greater than 82, the strong force is no longer enough to keep the nucleus together. In these cases, there is simply too much electrostatic repulsion from the protons in the nucleus that it cannot be contained. Once this is the case, we say that a nucleus is **unstable**.

unstable
describes a nucleus that is likely to decay because the strong nuclear force is not large enough to overcome the electrostatic repulsion force

Stability curve

The stability of a nuclide is described by the stability curve (Figure 6.4.1). Each dot on this curve represents a stable nuclide, with a corresponding number of protons and neutrons in the nucleus. It can be noted that as the atomic number increases, there must be more neutrons in the nucleus for the nuclide to be considered stable (where the nucleus is still in its ground energy state).

FIGURE 6.4.1 The stability curve. Each dot represents a stable nuclide. Note that the more neutrons there are in the nucleus, the greater the neutron to proton ratio.



A nucleus that is unstable (one that is not a dot on the line of stability curve) will undergo **radioactive decay** and emit radiation. *How* the nucleus is unstable will determine the type of decay it will undertake. Instability in nuclides is the result of too many protons, too many neutrons, or too many of both within the nucleus. The balance of the strong force and electrostatic force must be just right in order for the nucleus to remain in its ground state. The types of decay that nuclei undergo will be discussed in the next chapter.

radioactive decay
when a nucleus breaks apart, it can happen naturally or be forced by impact from subatomic particles outside the nucleus

SECTION REVIEW 6.4

REMEMBERING

1 State what it means for a nucleus to be stable.

2 Define the 'line of stability'.

UNDERSTANDING

3 If a nuclide has 10 protons and 90 neutrons, would it be considered stable? Explain your answer.

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CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 Define the following terms.
   a Nucleus
   b Atom
   c Subatomic particles
   d Electron
   e Neutron
   f Proton
   g Alpha particle
   h Nucleon
   i Element
   j Isotope
   k Nuclide
   l Atomic number
   m Mass number
   n Atomic weight
   o Strong nuclear force
   p Unstable

2 Name the subatomic particles within an atom.

CATEGORY QUESTIONS

3 Explain how a nucleus stays together despite the repulsive forces the protons exert on each other.

4 Explain the difference between an isotope and an element.

5 Explain how isotopes are named in order not to confuse different isotopes of the same element.

ELABORATION QUESTIONS

6 Explain why the strong nuclear force is considered the strongest force in the universe. Is this true in all cases?

7 Why does the net charge on an atom not define the element?

8 Explain what causes nuclides to be unstable.

EVIDENCE QUESTIONS

9 What evidence do we currently have that has allowed us to accept the Bohr–Rutherford model of the atom?

10 Carry out research on the newly postulated fifth fundamental force of the universe. What evidence is there to support this new force, and how will this reshape our understanding of physics if this theory becomes accepted?

END-OF-CHAPTER EXAM

End-of-chapter test

1 The nucleus is composed of:

A neutrons and electrons.

B neutrons and protons.

C protons and electrons.

D nucleons and electrons.

2 Isotopes of elements have similar properties. Which characteristic do all isotopes of the same element share?

A Number of electrons

B Energy level of the nucleus

C Number of nucleons

D Number of protons

3 The element represented by $^{77}_{34}X$ is:

A iridium.

B technetium.

C selenium.

D roentgenium.

4 Two protons are placed very close to each other. The force of electrostatic repulsion is measured to be F. Next, the distance between the two protons is quadrupled. What is the new force of electrostatic repulsion acting on the protons?

A $\frac{F}{2}$

B $\frac{F}{4}$

C $\frac{F}{8}$

D $\frac{F}{16}$

5 Name the isotope that has 37 protons and 85 nucleons.

6 Two protons in close proximity experience a repulsive electrostatic force, and an attractive gravitational force. Which force is larger?

7 Taking into account both mass and separation distance, which of the four fundamental forces is the strongest?

8 What does it mean for a nucleus to be stable?

9 Calculate the relative atomic mass of pure lithium if a sample contains 7.5% of lithium-6 and 92.5% of lithium-7.

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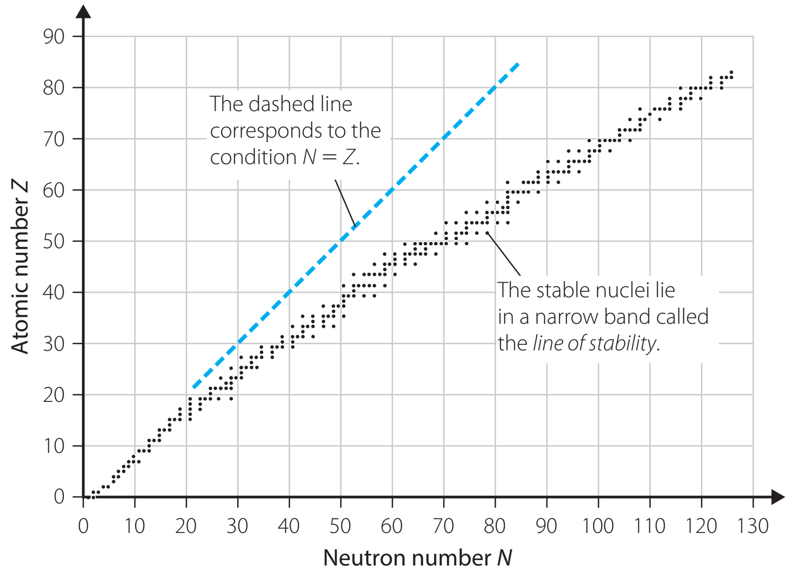
10 Referring to the stability curve below, would the isotope with 20 protons and 70 nucleons be stable? Why or why not?



11 Are protons, neutrons and electrons the smallest particles of matter or are they, in turn, be composed of yet smaller particles? Justify your response.

7 SPONTANEOUS DECAY AND HALF-LIFE

Introduction

Radiation that comes from the nucleus of an atom is called radioactivity. Radioactivity is in our everyday lives: it is used in medical diagnosis and treatment; every house is fitted with smoke detectors that use a radioactive source; leaks in pipes are traced using radioactivity, and radioactivity plays an enormous role in nuclear energy production.

Stimulus question

How do elements change their properties and turn into other elements?

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7.1 Natural radioactive decay

Radiation refers to energy transfer that occurs across space. Sunlight, for example, is radiation that travels from the Sun to Earth. It is experienced in a variety of ways, such as light and heat. Radiation can be classified in several different ways and distinguished by the effects it has on atoms. Some radiation originates on Earth, and other radiation bombards us from outer space and the upper atmosphere. This radiation is commonly referred to as **radioactivity**.

radiation
energy transfer across space; the process by which heat is transferred without the need for a medium; energy from radioactive atoms

radioactivity
particles or rays that come from energy rearrangements in a nucleus

gamma rays
high-energy electromagnetic radiation

non-ionising radiation
electromagnetic radiation that does not ionise nearby atoms and has low energy

ionising radiation
electromagnetic radiation that does ionise nearby atoms and has high energy

Non-ionising and ionising radiation

Radiation is also used to describe the emissions from radioactive atoms. **Gamma rays** are electromagnetic in nature, but alpha and beta radiation are charged particles with mass.

Some forms of radiation can ionise atoms by removing electrons. Radiation comes in two forms: **non-ionising radiation** and **ionising radiation**. Radiation from radioactive sources is ionising radiation; but electromagnetic radiation can be non-ionising or ionising depending on its energy.

Electromagnetic radiation is pure energy with no mass. It is modelled as continuous waves or massless particles called photons that have an associated wavelength. The **electromagnetic spectrum** is the entire range of wavelengths or frequencies of electromagnetic radiation from high-energy gamma rays to lower-energy radio waves, including visible light (Figure 7.1.1).

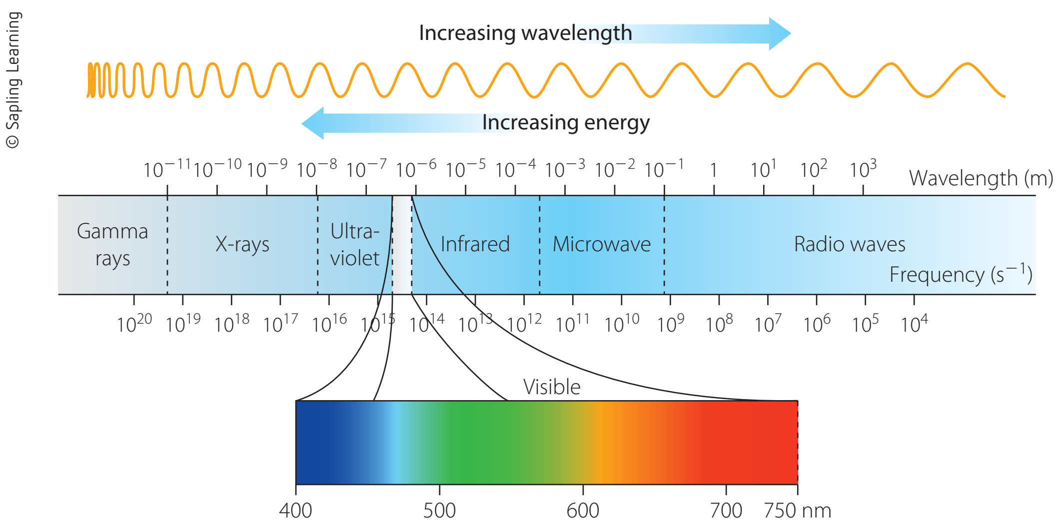


FIGURE 7.1.1 Electromagnetic spectrum, classifying radiation from high energy (ionising) to low energy (non-ionising)

Non-ionising radiation

Non-ionising radiation is electromagnetic radiation with low energy. Examples of sources of non-ionising radiation include electric power lines, microwave ovens, televisions and the light from the Sun. These radiations may affect our bodies for good or ill, but they do not change the electron configuration around the nuclei of atoms.

INQUIRING FURTHER

Research how non-ionising radiation pass through bodies without causing the electron configuration to change.

Ionising radiation

Ionising radiation is high-energy radiation that can affect the electrons surrounding an atom so that a charged ion is formed. Ionising radiation includes alpha particles, beta particles, gamma rays and X-rays.

electromagnetic spectrum
the continuous spectrum describing all radiation from high energy to low energy and including visible light

The high-energy nature of these types of radiation can affect our bodies in significant and unwanted ways, including changing the electron configurations, types of atoms, and radioactive materials in our bodies. We are constantly exposed to low-level, background ionising radiation from sources such as metals in Earth's crust and ultraviolet light from the Sun.

Background radiation

There are two types of background radiation: terrestrial radiation and cosmic radiation. Some terrestrial radiation comes from the decay of radioactive elements, such as uranium and thorium, in Earth's crust. The energy from radioactive decay of these materials is one of the factors contributing to the temperature of Earth. Terrestrial radiation can enter our food chain via the naturally occurring radioactive chemicals in soils.

Cosmic radiation comes to us from space. It is comprised mainly of protons (hydrogen nuclei) that interact with Earth's atmosphere to produce cosmic showers of radiation, some of which reach Earth's surface.

The background radiation on Earth varies in different locations. It depends on altitude and proximity to radioactive minerals. Radioactive fallout from nuclear tests and damaged nuclear power stations also adds to background radiation. These doses are usually small unless you are close to the site. The further you are from these additional sources of radiation, the lower the intensity of the background radiation.

INQUIRING FURTHER

There are many ways in which ionising radiation is harnessed for positive outcomes. Research these and explain how, even though ionising radiation is harmful to humans, it can benefit us.

PRACTICAL ACTIVITY 7.1.1

Background ionising radiation

AIM

To investigate the random nature of background radiation, and measure the background radiation rate

MATERIALS

- Geiger–Muller (G-M) tube, or Geiger counter

PROCEDURE

Set up the G-M tube to record counts every 15 seconds. Record the readings in a properly constructed data table.

ANALYSIS OF RESULTS

1 Produce a frequency table from the data table.
2 Plot a graph of count rate versus time.
3 Show the mean and standard deviation on the graph.

DISCUSSION

1 How does the graph of frequency against count rate demonstrate the random nature of background radiation?
2 Provide an estimate of the average background radiation per minute.

SECTION REVIEW 7.1

REMEMBERING

1 List the two main forms of radiation.

2 List the two origins of background radiation.

UNDERSTANDING

3 Explain why electromagnetic radiation is classified as both ionising and non-ionising.

4 Propose why the electromagnetic spectrum categorises different waves based on their energy.

APPLYING

5 Why is it useful to know the background radiation when doing radiation counting experiments? What would have to be done to the data before determining how much radiation is coming from the source?

ANALYSING

6 Terrestrial radiation keeps Earth's surface warm. Research how this happens and explain why other planets in our solar system are unable to achieve this.

7 Research two professions that would need to monitor their radiation exposure and explain how this exposure is monitored.

7.2 Types of radioactivity

Henry Becquerel (1852–1908) was the first scientist to discover that radiation was being emitted from atoms. In 1896 he identified that uranium salts emitted a previously unknown form of radiation. He called this *metal phosphorescence*, as he thought these emanations were an invisible form of light.

Becquerel discovered that this radiation was in fact small particles being emitted from the uranium atoms. Further exploration showed that there were different types of particles being emitted. When a radioactive nucleus emits an alpha or beta particle, it breaks into two parts – the lighter, emitted particle and a new nucleus of a different element. The original unstable element (**parent nuclide**) has decayed into a new element (**daughter nuclide**), which is more stable. This process is known as **radioactive decay** and occurs naturally until a daughter element is one of the stable nuclides defined on the line of stability.

When a parent nucleus decays to become more stable, it emits radiation. This is in the form of alpha particles, beta particles or gamma radiation. These types of radioactivity are summarised in Table 7.2.1.

parent nuclide the original nuclide before emitting particles from the nucleus

daughter nuclide the nuclide formed after a parent nuclide has emitted particles from its nucleus; the daughter nuclide is more stable than the parent nuclide

radioactive decay also called nuclear transformation, disintegration and transmutation; occurs when particles are emitted from the nucleus of an atom, causing it to change into a new nuclide; can happen naturally or be forced by impact from subatomic particles outside the nucleus

TABLE 7.2.1 Summary of types of radioactivity and their respective symbols

Alpha particle	α, ${}^{4}_{2}He^{2+}$	Helium-4 nuclide
Beta particle	β^-, ${}^{0}_{-1}e$	Electron
	β^+, ${}^{0}_{+1}e$	Positron
Gamma ray	γ, ${}^{0}_{0}\gamma$	Electromagnetic radiation
Neutrino	ν_e, ${}^{0}_{0}\nu_e$	Energy carrier
Antineutrino	$\bar{\nu}_e$, ${}^{0}_{0}\bar{\nu}_e$	Energy carrier

KEY FORMULA

Alpha decay can be written as

$^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha$

Where:

A = mass number

Z = proton number

X = the element before decay

Y = the element after α decay

Alpha decay

Alpha radiation is the largest particle that can be emitted from a nucleus. The particle is a positively charged helium nucleus, which contains two protons and two neutrons. It has been stripped of its two electrons, so it carries a +2 charge. The most common nuclide of uranium, $^{238}_{92}U$, undergoes decay, resulting in 90 protons and 234 nucleons in the daughter nucleus. The daughter nucleus is $^{234}_{90}Th$, thorium-234, and is a more stable nuclide than the uranium-238 parent nuclide. The nuclear equation for this decay is written as follows:

$$^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}\alpha$$

This could be alternatively be written as:

$$^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He^{2+}$$

In all radioactive decay, energy is released. In this example, the energy is almost all taken away by the alpha particle.

7.2.1 Alpha decay

Alpha decay occurs when a nucleus is unstable because it has too many nucleons. By ejecting two protons and two neutrons in the form of a helium nucleus, the daughter nuclide will be more stable.

WORKED EXAMPLE 7.2.1

Neptunium-237 decays by emitting an alpha particle and changes to a different element.

a Write a complete nuclear reaction equation that includes the symbol for the daughter nuclide.

b What is the name of the daughter nuclide?

ANSWERS

a Locate neptunium on the periodic table; its atomic number is 93.
The decay of neptunium is written as: $^{237}_{93}Np \rightarrow {}^{233}_{91}Pa + {}^{4}_{2}\alpha$

b The daughter nuclide is protactinium-233.

Beta decay

Beta radiation is particle radiation from the nucleus, but the particle is much smaller in mass than an alpha particle. There are two forms of beta decay: electron and positron emission. An electron has the opposite charge to a proton, and isn't a nucleon. Its symbol is written as $^{0}_{-1}e$ or $^{0}_{-1}\beta$ or simply β^{-}.

A positron is an anti-electron. It is the same mass as an electron, but has a positive charge of 1.6×10^{-19} C; that is, a positron is a positively charged electron. Its symbol is written as $^{0}_{1}e$ or $^{0}_{1}\beta$ or simply β^{+}.

7.2.2 Beta decay

The mass of both beta particles is very small compared to the mass of nucleons. They have a mass of 9.11×10^{-31} kg, which is tiny compared to a proton (1.6726×10^{-27} kg) or a neutron (1.6749×10^{-27} kg). These masses are summarised in Table 7.2.2.

TABLE 7.2.2 Summary of subatomic particles, alpha and beta particles, showing their respective masses and net charge

PARTICLE	MASS (kg)	CHARGE
Proton	1.6726×10^{-27}	Positive
Neutron	1.6749×10^{-27}	Zero
Alpha	6.644×10^{-27}	Positive
Electron	9.11×10^{-31}	Negative
Positron	9.11×10^{-31}	Positive

Electron emission

The ejection of an electron from the nucleus, β^- decay, can be modelled by regarding a neutron as capable of emitting an electron and turning into a proton. In this process, another particle known as an antineutrino, $\bar{\nu}$, is also emitted. An antineutrino is uncharged and almost undetectable.

antineutrino a very small particle that accompanies β^- decay

The nuclear equation for β^- decay can be written as ${}^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e + \bar{\nu}$ or ${}^{1}_{0}n \rightarrow {}^{1}_{1}H + {}^{0}_{-1}\beta + \bar{\nu}$.

A proton can be written as a hydrogen nucleus in the same way that an alpha particle can be written as a helium nucleus. They have the same atomic and mass numbers.

When thorium-234 undergoes β^- decay, it becomes the nuclide with 91 protons but an unchanged mass number of 234. The new element is protactinium, Pa: ${}^{234}_{90}Th \rightarrow {}^{234}_{91}Pa + {}^{0}_{-1}\beta + \bar{\nu}$.

Note that the electron is being emitted from the nucleus, not from the atomic shells. Also note that the mass number in beta decay remains unchanged – the number of nucleons has not been altered.

KEY FORMULA

β^- decay can be represented as ${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}\beta + \bar{\nu}$

Where:

A = mass number

Z = proton number

X = the element before decay

Y = the element after β^- decay

$\bar{\nu}$ = an antineutrino

Positron emission

The ejection of a positron from the nucleus, β^+ decay, can be modelled by regarding a proton as capable of emitting a positron and turning into a neutron. In this process, another particle known as a neutrino, ν, is emitted. Just like an antineutrino, a neutrino is uncharged and almost undetectable.

The nuclear equation for β^+ decay can be written as ${}^{1}_{1}p \rightarrow {}^{1}_{0}n + {}^{0}_{1}e + \nu$ or ${}^{1}_{1}H \rightarrow {}^{1}_{0}n + {}^{0}_{1}\beta + \nu$.

When thallium-195 undergoes β^+ decay, it becomes the nuclide with 80 protons but an unchanged mass number of 195. The new element is mercury, Hg: ${}^{195}_{81}Tl \rightarrow {}^{195}_{80}Hg + {}^{0}_{1}\beta + \nu$.

Note that the positron is being emitted from the nucleus, and that the mass number remains unchanged as no nucleons have been emitted.

KEY FORMULA

β^+ decay can be represented as ${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{1}\beta + \nu$.

Where:

A = mass number

Z = proton number

X = the element before decay

Y = the element after β^+ decay

ν = a neutrino

Beta emission modelling

Both β^- and β^+ emission models suggest that neutrons are composed of a proton and an electron, and that protons are composed of a neutron and positron. It is more accurate to assume that in an unstable nucleus, the nucleons can *convert* into these two particles and emit beta particles to become stable.

neutrino a very small particle that accompanies β^+ decay

Gamma emission

Gamma radiation is very high energy radiation. Gamma rays are not particles, but rather contain packets of energy that can be released from a nucleus in order for the nucleus to return to its ground state.

After a nucleus has undergone a transmutation, the daughter nuclide is left in an excited state. A very large amount of energy is then given off in the form of gamma rays and the nucleus returns to its ground state; hence it becomes more stable.

transmutation the conversion of one chemical element into another as the result of a nuclear reaction, such as neutron capture, or that occurs in spontaneous radioactive decay, such as alpha decay and beta decay

7.2.3 Properties of radiation

Gamma radiation does not change the mass number or the atomic number of an atom as it is not a particle. When a nuclide undergoes gamma emission, we write the following: ${}^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X + \gamma$.

Often but not always, the gamma radiation will be simultaneous with the alpha and beta radiation.

WORKED EXAMPLE 7.2.2

What daughter nuclide is produced after:

a alpha decay of a polonium-214 nuclide?

b β^{-} decay of carbon-14?

c positron emission from sodium-20?

d gamma emission from cerium-139?

ANSWERS

a ${}^{218}_{84}\text{Po} \rightarrow {}^{214}_{82}\text{Pb} + {}^{4}_{2}\alpha$

The daughter nuclide is lead-214.

b ${}^{14}_{6}\text{C} \rightarrow {}^{14}_{7}\text{N} + {}^{0}_{-1}\beta$

The daughter nuclide is nitrogen-14.

c ${}^{20}_{11}\text{Na} \rightarrow {}^{20}_{10}\text{Ne} + {}^{0}_{1}\beta$

The daughter nuclide is neon-20.

d ${}^{139}_{58}\text{Ce}^{*} \rightarrow {}^{139}_{58}\text{Ce} + \gamma$

The daughter nuclide is cerium-139.

SECTION REVIEW 7.2

REMEMBERING

1 When writing nuclear equations, which two numbers must be the same before and after radioactive decay?

2 Write the general equation for alpha, β^{-}, β^{+} and gamma emission.

UNDERSTANDING

3 Compare and contrast nuclear reactions and chemical reactions.

4 Fluorine-21 is a β^{-} emitter; identify the daughter nuclide.

APPLYING

5 Holmium-151 decays by alpha emission. Write a nuclear equation showing this process and name the daughter nuclide.

6 Radon-210 decays into polonium-206. What type of radioactive particle is emitted during this decay? Write the decay equation.

7 Francium-211 decays by emitting an alpha particle and changes to a different element.

- **a** Write a complete nuclear reaction equation that includes the symbol for the daughter nuclide.
- **b** Identify the daughter nuclide.

8 Polonium-213 decays by emitting an alpha particle and changes to a different element.

- **a** Write a complete nuclear reaction equation that includes the symbol for the daughter nuclide.
- **b** Identify the daughter nuclide.

ANALYSING

9 Use the correct symbols to show the decay of terbium-158 by alpha emission followed by gamma emission.

10 Gold-198 decays to mercury-198. Write the nuclear decay equation and identify the radioactive particle emitted during this process.

7.3 Properties of radiation

Alpha, beta and gamma radiation have the ability to affect matter. They each have a unique power to ionise and penetrate different materials.

ionising power the ability to ionise nearby atoms; high ionising power means it is likely for nearby atoms to have their electrons stripped

penetrating power the ability to penetrate air, liquids and solids; radiation with high penetrating power can penetrate highly compacted solids

Ionising power

Atoms become ions by losing or gaining electrons. If an atom loses electrons it becomes a positive ion, if it gains electrons it becomes a negative ion. Negative beta particles are repelled by electrons in atoms. This causes particles to be bounced around, causing collisions that, in turn, bump other electrons out of their atomic shells. These collisions transfer less energy than the interactions between alpha particles and atoms.

Positrons interact with electrons in atoms in a slightly different manner. As positrons attract electrons in the outer shells, it is possible for electrons to be ejected by attraction to a positron as well as a collision from beta-plus decay. Again, this type of collision transfers far less energy than the interactions between alpha particles and atoms. Both types of beta particle have the ability to ionise atoms. As beta particles are the same size as electrons, the collisions are rare.

Gamma radiation has the ability to ionise atoms by transferring all its energy to an electron, giving the electron enough energy to eject from the atom. This leaves behind a positive ion. The electron that is ejected may remain free for some time before binding to another atom or molecule.

Alpha particles have far more **ionising power** than beta particles and gamma radiation. As alpha particles are much larger, and have twice the charge, it is easy for an alpha particle to collide with electrons, and to draw electrons away by electrostatic attraction.

In order, the ionising power of radioactive particles is alpha, beta, gamma. This is inversely proportional to the **penetrating power** of these particles. This is to be expected because the particles expend their energy in causing ionisation, and hence do not penetrate as far. Neutrinos and antineutrinos are weakly interacting particles that do not ionise atoms.

Penetrating power

One of the easiest ways to compare the penetrating power of alpha, beta and gamma radiation (Figure 7.3.1) is by looking at what it takes to block them (Figure 7.3.2). It only takes paper to block alpha particles, aluminium to block beta particles and lead to block gamma radiation. It also helps to think about the size of these particles when thinking of their penetrating power as well. It is easier to block something larger (Figure 7.3.3).

Neutrons are highly penetrating in air and most other materials as they are uncharged. They are absorbed readily by materials containing a lot of hydrogen. Hence, water and concrete are excellent neutron absorbers and are used to help shield nuclear reactions.

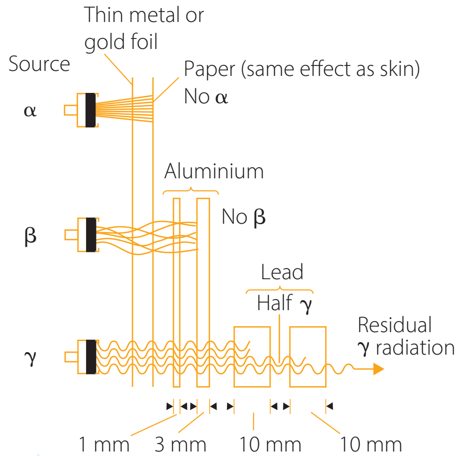


FIGURE 7.3.1 Gamma rays are the most penetrating type of nuclear radiation, followed by beta particles then alpha particles.

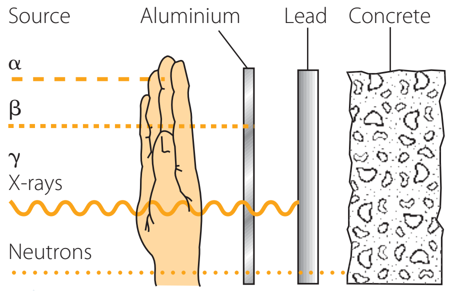


FIGURE 7.3.2 Penetrating power of different radiations. Notice that the alpha particles are easily blocked, and they are also the particle with the most net charge, mass and volume.

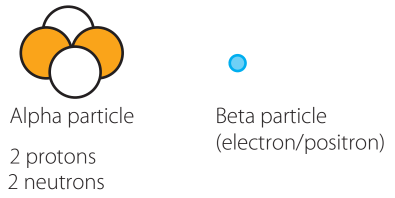


FIGURE 7.3.3 Representative size of alpha particle compared to beta particle. Not to scale.

INQUIRING FURTHER

Many nuclear power plants shield the nuclear reactions with large amounts of concrete and water. After a magnitude 9.0 earthquake in 2011, the Fukushima power plant in Japan was greatly damaged, and radiation began to leak out. Research the design of this power plant and explain how the concrete and water failed as a nuclear shield shortly after this incident.

Range in air

As their penetrating power suggests, alpha particles will not travel very far in air; beta particles will travel a range of distances depending on whether they collide with anything, and gamma radiation will travel infinitely far. There are many ions and other charged particles in air, which is what causes the alpha and beta particles to come to a halt. Examples of these include evaporated water, salts and ionisation from nearby thunderstorms, which can also ionise particles in air. Alpha particles will come to a stop after a few centimetres in air, whereas beta particles will stop after a few metres, depending on how much energy the particles have.

Effects of electric and magnetic fields on radiation

Charged alpha and beta particles moving in straight lines can be deflected in regions subject to electric or magnetic effects. Gamma rays have no mass or charge, which is why they are not deflected in either region. Charged particles are affected by electric and magnetic fields. Electric fields act on all charged particles, and magnetic fields act on moving charged particles. Charged particles emitted from nuclei are generally travelling very fast. Scientists can use electric and magnetic fields to distinguish between the different types of radiation.

Radiation in electric fields

As alpha and beta particles are both charged, they are affected by electric fields. Electric fields always indicate the direction in which a positive charge will move. This means that both alpha and β^+ particles will be accelerated in the direction of the electric field, and β^- particles will be accelerated in the opposite direction. The force that acts on each of these particles when it enters the field depends on its charge, and the magnitude of acceleration depends on both the charge and the mass. An alpha particle will accelerate more slowly and travel a path with less curvature than the β^+ particle, due to its greater mass. Gamma radiation is not charged and will pass through an electric field with no deflection (Figure 7.3.4).

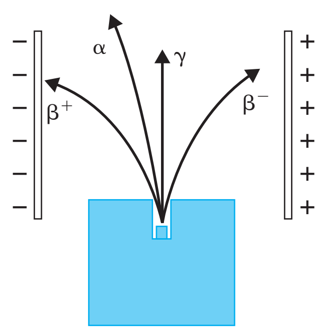
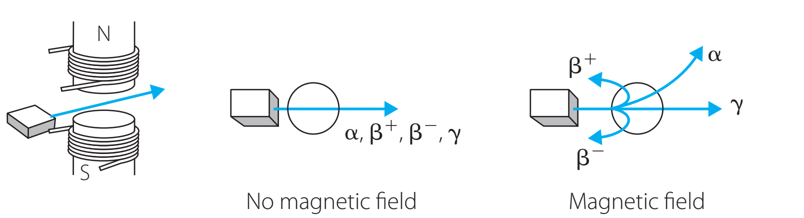


FIGURE 7.3.4 Charges in an electric field. Notice that the radius of deflection of the beta particles is much smaller than that of alpha particles. Gamma radiation is unaffected by an external electric field.

Radiation in magnetic fields

A magnetic field applies a force on any moving charged particle, so that the particle follows a curved path. The magnitude of the force depends on the speed at which the particle is moving and the magnitude of its charge. The direction of the force depends on the sign of the charge. Hence the force experienced by a β^+ particle is the same size but opposite in direction to that experienced by a β^- particle, if they are moving at the same speed. An alpha particle at the same speed experiences a force in the same direction as a β^+ particle, but will again experience less deflection (Figure 7.3.5). Gamma radiation does not have a charge, and so it will not be deflected in a magnetic field.

FIGURE 7.3.5 Deflections of radiation in a magnetic field. As in an electric field, the beta particles are deflected much more dramatically than the alpha particles, due to their smaller mass.



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The properties of alpha, beta and gamma radiation are summarised in Table 7.3.1.

TABLE 7.3.1 Properties of alpha, beta and gamma radiation

	α PARTICLES	β PARTICLES	γ RAYS
Nature	A helium nucleus (i.e. two protons and two neutrons)	A fast-moving electron or positron	High-frequency (short wavelength) electromagnetic radiation (i.e. a high-energy photon)
Charge	+2 elementary charges	−1 (electron) +1 (positron) elementary charge	Uncharged
Mass	4 atomic mass units (4 u) or $4 \times 1.66 \times 10^{-27}$ kg	0.0005 u 9.11×10^{-31} kg	No mass
Ionising effect	Strong	Weak	Very weak
Penetration	Few centimetres in air	Few metres in air	Very weakly absorbed in air (most radiation absorbed by a few centimetres of lead)
Effect of electric and magnetic fields	Very small deflection	Large deflection	No deflection
Typical emission velocity	5–7% of speed of light	30–90% of speed of light	Speed of light 3×10^8 m s^{-1}

Detection of radioactivity

Radioactive decay and particle emission is invisible. A number of different devices have been developed to detect the radiation. A charged electroscope can be used easily for this purpose. Solid-state detectors, dosimeters and thermoluminescent dosimeters (TLDs) are also used to detect and measure radiation. Other devices include the cloud chamber, the Geiger–Müller (G-M) tube and the Geiger counter.

To detect radiation today, a Geiger counter is commonly used. A Geiger counter consists of a G-M tube. It is an instrument for measuring radioactive emissions by detecting the ionising radiation nearby. The basic design for a G-M tube is seen in Figure 7.3.6. Radiation enters the mica window and ionises the argon gas inside the tube. This causes the free electrons to electrically pulse towards the anode, where they are collected by the wire. This collection is then measured to determine the number of radioactive particles that originally entered the G-M tube through the mica window by counting the number of pulses.

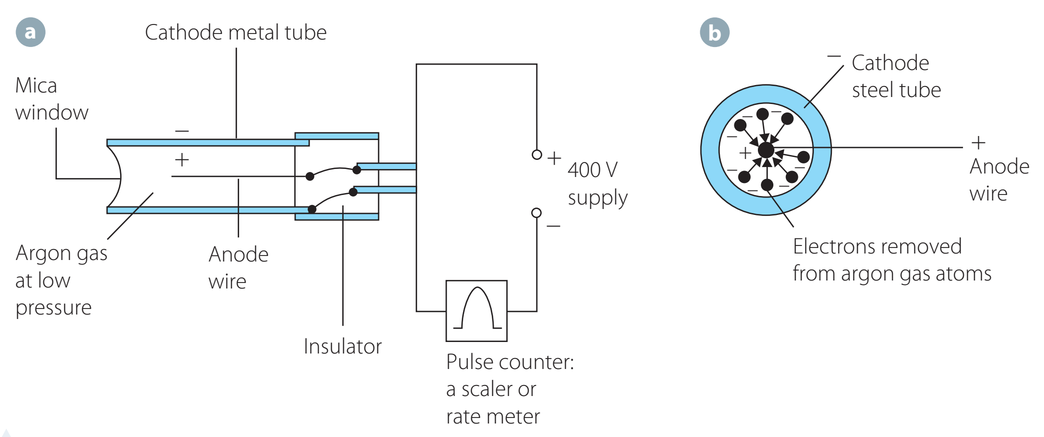

FIGURE 7.3.6 The basic set-up of the inside of a Geiger counter. The counter uses a circuit to detect how many electrons hit the anode and hence determine how many radioactive particles entered the tube.

SCIENCE AS A HUMAN ENDEAVOUR

Explore how scientific knowledge of radioactive decay can enable scientists to offer valid explanations and make reliable predictions in radiometric dating of materials.

INQUIRING FURTHER

There are other ways to measure the number of radioactive particles; the G-M tube is just the most common. Research the other devices mentioned above and, using a diagram, write an explanation of how each one measures radioactivity.

From this, the *count rate* can be determined by dividing the number of counts (pulses) by the time interval.

$$\text{Count rate} = \frac{\text{number of counts}}{\text{time interval}}$$

The number of counts is the number of electric pulses the G-M tube counts, and the time interval is the period of time for which these counts are collected (in seconds, minutes etc.).

SECTION REVIEW 7.3

REMEMBERING

1 State which type of radiation is:

- **a** most penetrating
- **b** most ionising
- **c** most likely to cause damage.

2 Which two types of radiation are deflected in the same direction in a magnetic field?

UNDERSTANDING

3 Which type of radiation is not deflected at all in either electric or magnetic fields? Why?

4 Identify the type of radiation that is least deflected in electric and magnetic fields. Explain your answer.

APPLYING

5 A Geiger–Muller tube detects radiation by using a count rate. What does this mean?

ANALYSING

6 If 1600 counts are recorded in a G-M tube in 20 s, what is the count rate?

7.4 Predicting decay

Predicting what type of decay a nuclide may undergo in order to become stable depends on the type of nuclide. Some nuclides have too many protons, some have too many neutrons, and some have too many nucleons altogether within their nucleus. The nuclear make-up will determine the type of decay the nuclide will undergo.

If a nuclide has too many neutrons to be stable, it will undergo β^- decay, resulting in one less neutron and one more proton in the nucleus. If a nuclide has too many protons to be stable, it will undergo β^+ decay, resulting in one less proton and one more neutron in the nucleus. If the nuclide has too many nucleons (protons and neutrons) to be stable, it will undergo alpha decay in order to decrease both the number of protons and the number of neutrons in the nucleus.

These emissions can be represented with arrows on the line of stability (Figure 7.4.1). In each case, the tail of the arrow stems from the parent nuclide, and the tip of the arrow represents the daughter nuclide. The arrows will always point towards the more stable, daughter nuclide (Figure 7.4.1).

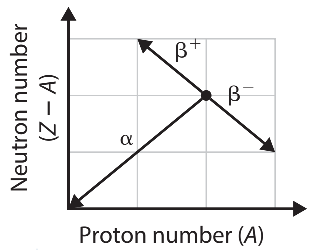

FIGURE 7.4.1 Arrows representing how to show decays on the line of stability

7.4.1 Predicting radioactive decay

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WORKED EXAMPLE 7.4.1

On the line of stability, use arrows to show the following decays. Write the decay equation for each. (Note: If you do not have a hard copy of the line of stability, draw a simple grid to represent the radioactive decay.)

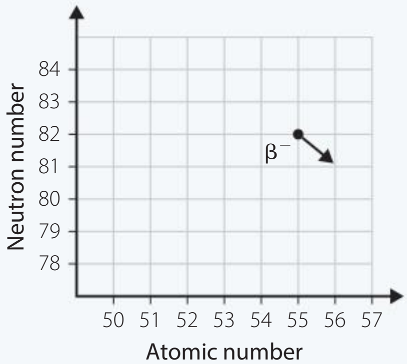
a The β^- decay of caesium-137

b The β^+ decay of magnesium-23

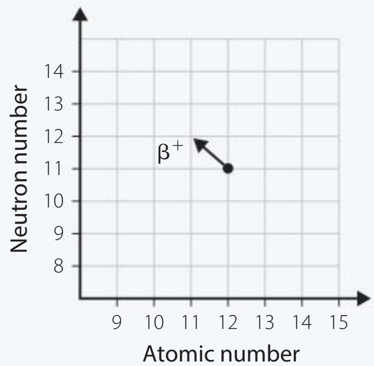
c The alpha decay of radon-222

ANSWERS

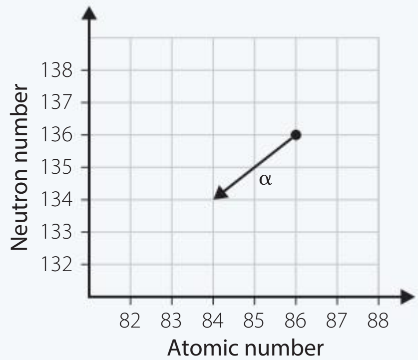
a $^{137}_{55}\text{Cs} \rightarrow {}^{137}_{56}\text{Ba} + {}^{0}_{-1}\beta$



b $^{23}_{12}\text{Mg} \rightarrow {}^{23}_{11}\text{Na} + {}^{0}_{1}\beta$



c $^{222}_{86}\text{Rn} \rightarrow {}^{218}_{84}\text{Po} + {}^{4}_{2}\alpha$



Artificial transmutation

Rutherford was the first to use radioactivity to produce new nuclides to make one element into another. He bombarded nitrogen-14 with alpha particles and analysed the result. Oxygen and hydrogen were formed. The reaction proceeded as follows: nitrogen nuclei absorb helium nuclei and form a composite, unstable nuclide, denoted by an asterisk: $^{14}_{7}\text{N} + {}^{4}_{2}\text{He} \rightarrow {}^{18}_{9}\text{F}^*$. The composite nuclide decays to a more stable state: $^{18}_{9}\text{F} \rightarrow {}^{17}_{8}\text{O} + {}^{1}_{1}\text{p}$ (Figure 7.4.2).

bombarding radiation
radiation composed of particles, such as alpha particles or neutrons, that are bombarded at the nucleus to force transmutation and radioactive decay

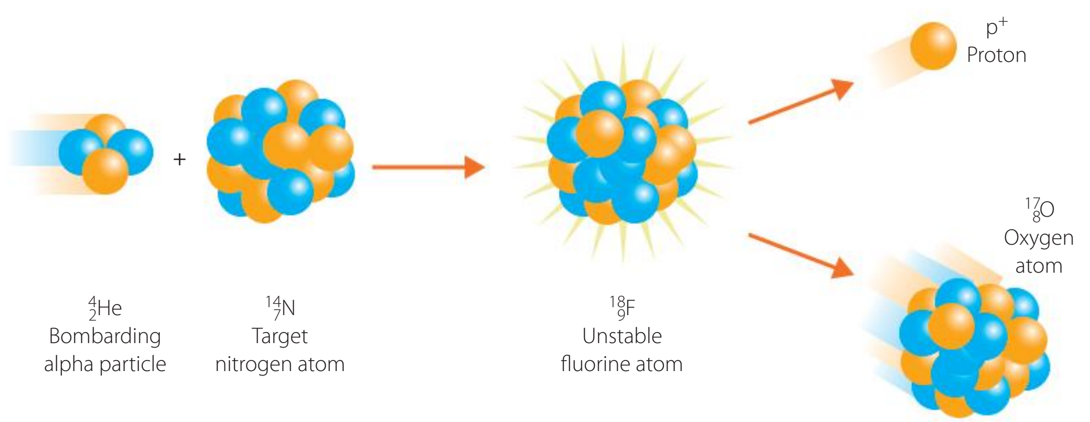


FIGURE 7.4.2 Diagram of the alpha bombardment of nitrogen

The discovery of the neutron enabled scientists to explore the behaviour of larger atomic nuclei. As it is neutral, the neutron is not repelled by the nucleus. It can be absorbed into the nucleus of the target atom. This makes it very useful as a form of **bombarding radiation**. It is used in many experiments to transmute a number of nuclides artificially. When a nucleus takes in a neutron it becomes less stable. Frequently, the nuclide becomes a beta-emitter. Bombarding uranium nuclei with neutrons delivered unexpected results. Capture of a neutron by a uranium nuclide can lead to two results: the nuclide can form a transuranic element or split into two nuclei of intermediate mass. Both of these results will release a large amount of energy.

transuranic element
an element that can only be produced synthetically, and does not exist naturally in the universe

Transuranic elements

Each element beyond uranium (atomic number 92) is a **transuranic element**. They do not exist naturally. All are produced artificially. All are radioactive. There are no known stable isotopes of any transuranic element. Some, such as plutonium and neptunium, have very long half-lives (more than 4 million years). Others, such as americium, berkelium and californium, are reasonably long-lived (800–34 000 years). Elements 109–118 have half-lives from minutes to milliseconds or less. Half-lives will be discussed later in the chapter.

SECTION REVIEW 7.4

REMEMBERING

1. Define 'transuranic element'.
2. Describe how the first two transuranic elements were produced.

UNDERSTANDING

3. Draw uranium-238 undergoing alpha decay on the line of stability and identify the daughter nuclide.
4. Draw protactionium-233 undergoing β^- decay on the line of stability and identify the daughter nuclide.

ANALYSING

5. Bombardment is used to artificially create elements. Research the positive and negative effects of artificially creating elements.

7.5 Balancing nuclear equations

When writing nuclear equations, it is important that the mass numbers and atomic numbers are balanced. Uranium-238 decays via alpha particle emission as follows:

$$^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\text{He}^{2+}$$

If the notation is used in which an alpha particle is written as a helium nucleus, as in this instance, it is unnecessary to write the 2+ in the right superscript. That is, the alpha decay of uranium-238 can be written in the following ways:

$$^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\text{He} \quad \text{or} \quad {}^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\alpha$$

After a nuclide has decayed, the daughter nuclide is left in an excited state before it emits gamma radiation. This gamma emission happens almost instantly (but not always) after radioactive decay. For uranium-238 the complete decay equation would be written as follows:

$$^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\alpha + \gamma$$

Note that gamma radiation will, in most cases, accompany both alpha and beta particle emission, and hence it is not necessary to include it in the decay equation.

Neutrinos and antineutrinos

An antineutrino and a neutrino accompanying β^- and β^+ decay respectively. The decay of thorium-234 is represented as follows:

$$^{234}_{90}\text{Th} \rightarrow {}^{234}_{91}\text{Pa} + {}^{0}_{-1}\beta + \bar{\nu} \quad \text{or} \quad {}^{234}_{90}\text{Th} \rightarrow {}^{234}_{91}\text{Pa} + {}^{0}_{-1}\text{e} + \bar{\nu}$$

and has an antineutrino accompanying the beta emission.

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The decay of thallium-195 can be written as:

$$^{195}_{81}\text{Tl} \rightarrow {}^{195}_{80}\text{Hg} + {}^{0}_{1}\beta + \nu \quad \text{or} \quad {}^{195}_{81}\text{Tl} \rightarrow {}^{195}_{80}\text{Hg} + {}^{0}_{1}\text{e} + \nu$$

and has a neutrino accompanying the beta emission.

Neutrino and antineutrino particles are always emitted with beta emission, and can be omitted when writing the nuclear decay equations for the purpose of determining the daughter nuclides. This means the decay of thorium-234 can be written simply as $^{234}_{90}\text{Th} \rightarrow {}^{234}_{91}\text{Pa} + {}^{0}_{-1}\beta$ and the decay of thallium-195 can be written as $^{195}_{81}\text{Tl} \rightarrow {}^{195}_{80}\text{Hg} + {}^{0}_{1}\beta$.

SECTION REVIEW 7.5

REMEMBERING

1 List the possible notations that can be used for alpha decay.

2 List the possible notations that can be used for the two types of beta decay.

APPLYING

3 The following elements undergo β^- decay. Use the periodic table to find the daughter nuclide and write a balanced nuclear equation for each.
   - a Magnesium-23
   - b Krypton-81
   - c Cesium-137

4 The following elements undergo β^+ decay. Use the periodic table to find the daughter nuclide and write a balanced nuclear equation for each.
   - a Carbon-11
   - b Iodine-121
   - c Oxygen-15

5 The following elements undergo alpha decay. Use the periodic table to find the daughter nuclide and write a balanced nuclear equation for each.
   - a Uranium-233
   - b Plutonium-240
   - c Radon-222

7.6 Using decay equations

So far, we have considered a parent nuclide decaying into a daughter nuclide through radioactive decay. This has only considered one atom. Typically, many atoms of a given element are found together, such as in an ore. Therefore, it needs to be considered that at any given point, any of those nuclides will decay into the daughter nuclide.

Although all unstable elements will decay to be stable, the point at which alpha or beta particles are emitted from the nucleus is entirely random. Spontaneous radioactive decay occurs naturally, and although it cannot be known exactly when a nuclide will decay, we can predict how long it will take for a percentage of the substance to decay.

This can be modelled as an exponential decay function: $N = N_0 e^{-\lambda t}$.

KEY FORMULA

Exponential decay function

$N = N_0 e^{-\lambda t}$

Where:

N = a unit of parent nuclides after time t

N_0 = the initial unit of parent nuclides at $t = 0$ s

t = time elapsed in s

λ = the decay constant in s^{-1}, unique to each nuclide

activity
a measure of the magnitude of radioactive emissions. Activity is simply the number of emissions per second, measured in the SI unit Bq

KEY FORMULA

$A = \lambda N$

Where:

A = the activity of a substance in Bq

λ = the decay constant in Bq (s^{-1})

N = the unit of the sample remaining when the activity is measured

Determining activity over time

Over time, as a radioactive substance decays, its **activity** decreases. This is simply due to there now being fewer unstable nuclides present. In fact, the activity of a radioactive sample (measured in becquerels, Bq, which is simply 'per second') is directly proportional to the amount of the sample remaining: $A \propto N$. The proportionality constant to equate these two variables is the decay constant λ, unique to each isotope.

As the amount of activity over time is directly proportional to how many parent nuclides remain after time t, it can also be modelled as an exponential decay function: $A = A_0 e^{-\lambda t}$. Graphing the activity after time t for any given nuclide results in the decay curve shown in Figure 7.6.1.

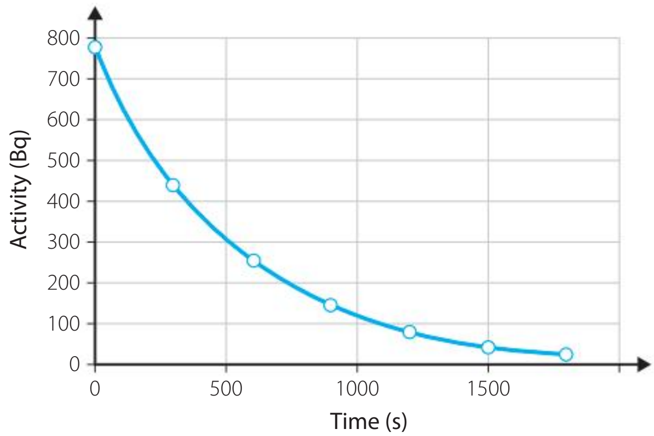

FIGURE 7.6.1 Graphical model of exponential decay. Note that the substance begins with a large activity, and over time it very quickly tends to zero. The time the substance takes to decay is unique to each nuclide.

WORKED EXAMPLE 7.6.1

Protactinium-234 has a decay constant of 9.9×10^{-3} Bq. Answer the following questions regarding the decay of protactinium.

a How much of a 2 kg sample of protactinium would remain after 300 s?

b If 700 g of a protactinium sample remains after two hours, how heavy was the original sample?

c Determine long would it take for a sample of protactinium to decay by half its original amount.

d Plot the decay of a 100 g sample of protactinium over 10 minutes. Use at least five data points.

ANSWERS

a State the equation for exponential decay:

$N = N_0 e^{-\lambda t}$

Substitute the known values:

$N = 2e^{-9.9\times10^{-3}\times300}$

Evaluate:

$N = 0.102$ kg remaining

b First, convert the time elapsed to seconds:

$2\text{ h} \times \frac{60\text{ min}}{\text{h}} \times \frac{60\text{ s}}{\text{min}} = 7200\text{ s}$

State the equation:

$N = N_0 e^{-\lambda t}$

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Rearrange to make N_0 the subject:

$$N_0 = \frac{N}{e^{-\lambda t}}$$

Substitute the known values:

$$N_0 = \frac{700}{e^{-9.9\times10^{-3}\times7200}}$$

Evaluate:

$N_0 = 6.33 \times 10^{33}$ g

$N_0 = 6.33 \times 10^{30}$ kg in the original sample

c When half of a sample remains, the ratio $\frac{N}{N_0} = 0.5$.

Write the equation:

$$N = N_0 e^{-\lambda t}$$

Rearrange:

$$\frac{N}{N_0} = e^{-\lambda t}$$

$$0.5 = e^{-\lambda t}$$

Rearrange for time:

$$\ln(0.5) = -\lambda t$$

$$t = -\frac{\ln(0.5)}{\lambda}$$

Evaluate:

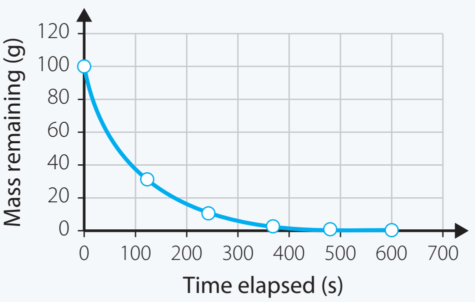
$$t = -\frac{\ln(0.5)}{9.9\times10^{-3}}$$

$$t = 70 \text{ s}$$

d Drawing a table of values will aid drawing a graph. Five data points are required to demonstrate the decay of protactinium over 10 minutes. Convert each data point to seconds, as the decay constant is given in Bq. The mass remaining is calculated after each time interval using the same method as in part **a**.

Time elapsed (min)	0	2	4	6	8	10
Time elapsed (s)	0	120	240	360	480	600
Mass remaining (g)	100	30.4	9.2	2.8	0.9	0.3

Plot these with N on the y axis, and t on the x axis, and draw a trend line.



SECTION REVIEW 7.6

REMEMBERING

1 Write the equation for exponential decay.

2 Define 'activity'.

APPLYING

3 Thallium-201 has a decay constant of 2×10^{-6} Bq. After 260 s, how much of a 1 kg sample remains?

4 After 27 years, a sample of plutonium-238 weighs 300 g. Plutonium-238 has a decay constant of 7.9×10^{-3} per year. How much of the sample was there to begin with?

5 After 1257 years, the activity of a sample of radium has reduced to 58% of what it was originally. What is the decay constant?

ANALYSING

6 Every two seconds, a sample of protactinium-225 decays by half. Originally, there were 1.6×10^{26} particles in the sample. Plot a graph of the decay of the protactinium sample over the first 12 s.

7.7 Stable nuclides

spontaneously happening without any external action; all radioactive materials decay spontaneously, in a random and unpredictable way, and it is impossible to predict when one atom will decay, if at all in a given time period

Nuclides will **spontaneously** decay to become more stable. In the case of very large nuclides, it will take more than one type of radioactive decay for this to happen. Consider uranium-238; it decays by alpha emission to become thorium-234, but thorium-234 is not a stable nuclide. Therefore, thorium-234 will also decay, most likely by β^- decay to protactinium-234. This process will continue until a stable nuclide is formed.

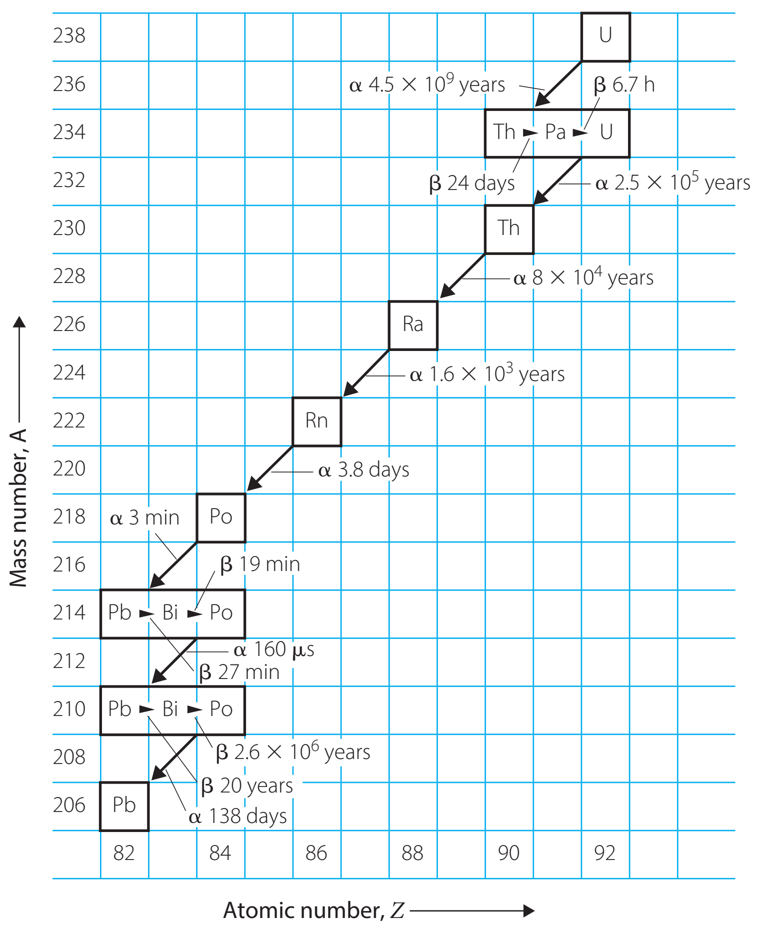
The starting nuclide will determine the decay process that the element is likely to go through to become stable. This decay process is represented as a decay series or decay chain. Decay series are graphical representations of the possible emissions daughter nuclides will go through to become stable, and a decay chain is a flow chart showing this process.

Decay series and decay chains

Many products of radioactive decay are themselves radioactive. Eventually, a stable end-product is reached and a number of these naturally occurring decay series have been identified. Three examples of these are:

1. radium or uranium series from uranium-238 to lead-206 (Figure 7.7.1)
2. actinium series from uranium-235 to lead-207
3. thorium series from thorium-232 to lead-208.

FIGURE 7.7.1 Radium decay series represented graphically. The half-life of each nuclide is stated, and gamma radiation is associated with many of these decays.



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The end product in each of these series is lead with $Z=82$. A fourth series, a neptunium series, starts at neptunium-237 and finishes at the stable nuclide thallium-205. Neptunium can only be produced artificially, and only two of its decay chain daughters occur naturally.

The nuclides in the radium series can be represented with the decay chain shown in Figure 7.7.2. Arrows are used to show the daughter nuclide that will result from the previous parent, until a stable nuclide is reached.

The nuclides in the radium series

parent: $^{238}_{92}U \rightarrow$

daughters: $^{234}_{90}Th \rightarrow ^{234}_{91}Pa \rightarrow ^{234}_{92}U \rightarrow ^{230}_{90}Th \rightarrow ^{226}_{88}Ra \rightarrow ^{222}_{86}Rn \rightarrow ^{218}_{84}Po$
$\rightarrow ^{214}_{82}Pb \rightarrow ^{214}_{83}Bi \rightarrow ^{214}_{84}Po \rightarrow ^{210}_{82}Pb \rightarrow ^{210}_{83}Bi \rightarrow ^{210}_{84}Po \rightarrow ^{206}_{82}Pb$

FIGURE 7.7.2 The decay chain for uranium-238 showing the daughter nuclides. This is a much more simplistic representation than a decay series, as the half-lives and types of decay are not represented.

WORKED EXAMPLE 7.7.1

The neptunium series begins with an alpha decay, followed by a β^- decay.

a Show the first two decays in the series in correct symbol form.

b Write in words the names of the two daughter nuclides.

ANSWERS

a $^{237}_{93}Np \rightarrow ^{233}_{91}Pa + ^{4}_{2}He$

$^{233}_{91}Pa \rightarrow ^{233}_{92}U + ^{0}_{-1}\beta$

b Daughter nuclides are protactinium-233 and uranium-233.

The different decay series are summarised in Table 7.7.1. There are four decay series but only three arise naturally.

TABLE 7.7.1 Decay series: cascade of decays from a radioactive nuclide until a stable nuclide is reached

NAME	START NUCLIDE	END NUCLIDE
Radium	$^{238}_{92}U$	$^{206}_{82}Pb$
Actinium	$^{238}_{92}U$	$^{207}_{82}Pb$
Thorium	$^{232}_{90}Th$	$^{208}_{82}Pb$
Neptunium	$^{237}_{93}Np$	$^{205}_{81}Tl$

SECTION REVIEW 7.7

REMEMBERING

1 List all the types of naturally occurring decay series.

2 Identify the atomic number of the stable nuclide that each decay series ends with.

3 Identify the decay series that arises from artificial transmutation.

UNDERSTANDING

4 Suggest a reason as to why there are no decay series named for starting nuclides with atomic number less than 82.

APPLYING

5 Write the decay equations for every transmutation in the radium series. Use Figure 7.7.1 (page 138) to aid you.

6 The thorium series begins with an alpha decay, followed by a β^- decay.

   a Show the first two decays in the series in correct symbol form.

   b Write in words the names of the two daughter nuclides.

7 The actinium series begins with an alpha decay, followed by a β^- decay.

   a Show the first two decays in the series in correct symbol form.

   b Write in words the names of the two daughter nuclides.

7.8 Half-life

half-life
the time it takes for half of a radioactive substance to decay

As radioactive decay is a random event, it is impossible to predict exactly when a certain isotope will decay, or even if it will decay at all in a given time period.

If there is a large enough sample of radioactive nuclei, then it can be said that some fraction of them will decay in a given time. The **half-life** of a radioactive substance is how long it takes for half the substance to decay.

In a 1 gram sample of uranium there are approximately 10^{20} unstable nuclei. In one half-life, half of these will decay. In the second half-life, half of the remaining nuclei decay. This means that after two half-lives only 25% of the original sample will remain.

In general, for a sample of N_0 particles, the number N remaining after n half-lives is given by the equation $N = N_0\left(\frac{1}{2}\right)^n$.

The half-life of a substance is given the symbol $t_{1/2}$. Each radioactive isotope has a unique half-life.

The decay constant is directly related to the half-life of an isotope:

$$t_{1/2} = \frac{\ln 2}{\lambda}.$$

KEY FORMULA

$$N = N_0\left(\frac{1}{2}\right)^n$$

Where:

N = a unit of parent nuclides after time t

N_0 = initial unit of parent nuclides at $t = 0$ s

n = number of half-lives that have elapsed

KEY FORMULA

$$t_{1/2} = \frac{\ln 2}{\lambda}$$

Where:

$t_{1/2}$ = half-life of the isotope

λ = decay constant

Note that if the decay constant is in Bq, the half-life will be in seconds.

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WORKED EXAMPLE 7.8.1

Krypton-89 has a half-life of approximately 4 minutes.

a How long will it take for a 74 g sample of krypton-89 to only have 12 g of the original isotope remaining?

b What is the decay constant for kyrpton-89?

ANSWERS

a First, determine how many half-lives this would take by rearranging $N = N_0\left(\frac{1}{2}\right)^n$ for n:

$$N = N_0\left(\frac{1}{2}\right)^n$$

$$\frac{N}{N_0} = \left(\frac{1}{2}\right)^n$$

$$n = \log_{\frac{1}{2}}\frac{N}{N_0}$$

Substitute in values:

$$n = \log_{\frac{1}{2}}\frac{12}{74} = \frac{\log\frac{12}{74}}{\log\frac{1}{2}}$$

$n = 2.62$ half-lives

Each half-life is 4 minutes long, and $4 \times 2.62 = 10.5$.
Therefore, it will take 10.5 minutes until only 12 g of krypton-89 remains.

b $t_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$

Rearrange for λ:

$$\lambda = \frac{\ln 2}{t_{\frac{1}{2}}}$$

$$\lambda = \frac{\ln 2}{4}$$

$\lambda = 0.17$ decays/minute

PRACTICAL ACTIVITY 7.8.1

Random decay and half-life: a simulation

AIM

To simulate random decay and half-life of a radioactive material.

MATERIALS

- a bag or cup
- 80 small counters or similar with an 'up' side and a 'down' side (such as M&Ms)
- clean surface

PROCEDURE

1. As a class determine which side of the counter represents decay (up) and which side represents not-decay (down).
2. Shake the bag and pour the counters onto a clean surface.
3. Record the number of counters that have *decayed* and move them to one side.
4. Replace the not-decayed counters back in the bag and repeat the process until no counters remain.

ANALYSIS OF RESULTS

1. Use whole class data to plot a graph of the number of counters remaining versus the number of trials.
2. From the graph, determine the half-life of the counters.

DISCUSSION

1. For radioactivity, how did this experiment model:
   a. the randomness of decay?
   b. half-life?
2. A radioactive nuclide is an unstable nucleus that could decay at any moment. The decay occurs because the daughter nuclide is more stable than the parent. Discuss.

EXTENSION

In this experiment, the half-life was one 'throw' of the counters. Try modelling a half-life that is less than one 'throw' by repeating this experiment using a large number of dice. What is the half-life when you remove all dice with a one showing at each throw? What if you remove all those with a one or a two showing?

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SECTION REVIEW 7.8

REMEMBERING

1 Define 'half-life'.

2 Write the equation that links the number of nuclides and the whole numbers of half-lives.

UNDERSTANDING

3 The half-life of polonium-218 is 3.0 minutes. A particular nuclide of polonium-218 has not decayed after 9.0 minutes. What are the chances that it will decay some time before 12 minutes?

APPLYING

4 The half-life of carbon-14 is 5730 years. What is its decay constant?

5 The half-life for thallium-200 is 1×10^4 s. A kilogram of thallium-200 contains close to 3.0×10^{24} atoms. After approximately one half-life, how many atoms in the original sample:

a have decayed?

b are still able to decay?

6 How many half-lives would it take for 30% of a sample to decay?

ANALYSING

7 The half-life of actinium-225 is 10 days. Plot the decay of actinium-225 over 100 days if the original sample is 500 g.

7.9 The big picture

Radioactivity has many positive and negative side effects. Radiation treatments are used in medicine, energy can be harnessed from transmutations for power, and, unfortunately, this energy can also be used for weapons of mass destruction. Radioactivity is also used to determine the age of fossilised biological material such as plants and animals.

Nuclear medicine

Nuclear medicine uses radiopharmaceuticals for medical diagnosis and treatment. In diagnosis, an external detector records the passage or localisation of a radioactive nuclide. Nuclear medicine treatment destroys cells and can also promote healing. This must be localised in order to not affect healthy tissues. The best radiation methods use gamma radiation with particular energies in order to destroy mutated cells before they replicate.

INQUIRING FURTHER

Research PET scans and how they are used to diagnose patients with different health problems.

SCIENCE AS A HUMAN ENDEAVOUR

Research how advances in scientists' understanding of nuclear radiation has influenced medical treatment and imaging. Explore the use of scientific knowledge to predict behaviour and/or harmful or unintended consequences of these medical applications. Be sure to consider the types of radioisotopes used and where radioactive waste is stored.

Radioactive dating

In the atmosphere, carbon-14 is only found in trace amounts. The ratio of carbon-14 to all other isotopes of carbon is $1{:}10^{12}$. When living organisms die, it is approximated that this is also the ratio of carbon-14 to other isotopes of carbon within their bodies. After the organism has died, no new carbon-14 is taken in, and the carbon-14 in the dead organism undergoes β^- decay and transmutes into nitrogen-14.

The half-life for carbon-14 is approximately 5730 years. If the amount of carbon-14 in a dead organism can be measured, it can be compared to the original ratio to determine the time since the organism died.

WORKED EXAMPLE 7.9.1

A sample of fossilised plant material found in the Kimberley was recently analysed, and it was found that only 45% of carbon-14 was present. If 100% represents the ratio $1:10^{12}$ of carbon-14 to carbon isotopes originally, how old is the sample?

ANSWER

Write the equation:

$$N = N_0\left(\frac{1}{2}\right)^n$$

Rearrange the equation and substitute known values:

$$\frac{N}{N_0} = \left(\frac{1}{2}\right)^n$$

$$0.45 = \left(\frac{1}{2}\right)^n$$

Rearrange for n and calculate the answer:

$$n = \log_{\frac{1}{2}} 0.45$$

$$n = 1.15 \text{ half-lives}$$

The half-life of carbon-14 is 5730 years.

$1.15 \times 5730 = 6570$ years

The sample is 6590 years old.

7.9.1 Radioactive dating game

Carbon-14 is commonly used for dating organisms that are thousands of years old, but other isotopes can also be used for radioactive dating. As long as the half-life of the isotope and its original abundance in living organisms is known, the age can be estimated. Some isotopes have half-lives of millions or billions of years, and are used when approximating the ages of fossils that are millions of years old. This reduces the source of error. Examples of such isotopes include uranium-235 and potassium-40.

SECTION REVIEW 7.9

REMEMBERING

1 What are some uses for radioactive isotopes?

UNDERSTANDING

2 Distinguish between diagnosis and treatment.

3 Why is half-life important when administering a radioisotope to a patient who needs to have a PET scan?

APPLYING

4 Explain why it is important to have a local source for radiopharmaceuticals.

5 Explain how carbon-14 is used to determine the approximate age of fossils of plants and animals.

ANALYSING

6 Would carbon-14 be a useful isotope for measuring how old something is if the organism is only hundreds of years old instead of thousands? Explain your answer.

CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 Define the following terms.
  a Radioactivity
  b Radiation
  c Non-ionising radiation
  d Ionising radiation
  e Alpha particle
  f Beta particle
  g Gamma ray
  h Parent nuclide
  i Daughter nuclide
  j Radioactive decay
  k Neutrino
  l Antineutrino
  m Ionising power
  n Penetrating power
  o Transuranic element
  p Half-life

2 State the types of radiation that are emitted as a result of radioactive decay.

CATEGORY QUESTIONS

3 Explain how the ionising power of each type of radiation differs.

4 Explain why it cannot be predicted when a single unstable nuclide will decay.

5 What uses does radioactivity have in the modern world?

ELABORATION QUESTIONS

6 Explain why an element with too many protons would not undergo β^- decay.

7 Why is it useful to know the half-life of an isotope?

8 Why is gamma radiation not deflected in either magnetic or electric fields?

EVIDENCE QUESTIONS

9 The current age of Earth is approximately 4.35 billion years. What evidence do we have to support this? How does radiometric dating help determine this age?

10 Background radiation experienced on Earth is from a variety of sources. Research background radiation and compile a list of the different sources of background radiation that we are exposed to on a day-to-day basis. How would this background radiation differ on Mars? How would your answer change if we had colonised Mars, and had inhabited it for over 100 000 years?

END-OF-CHAPTER EXAM

End-of-chapter test

1 An example of ionising radiation is:

A light from the Sun.

B microwaves.

C UV radiation from the Sun.

D heat from the Sun.

2 $^{168}_{77}\text{Ir}$ undergoes alpha decay. The daughter nuclide is:

A $^{164}_{75}\text{Re}$.

B $^{166}_{73}\text{Ta}$.

C $^{168}_{76}\text{Os}$.

D $^{168}_{78}\text{Pt}$.

3 The most common way to detect radioactivity is with which instrument?

A A G-M tube

B An isotope tracker

C An electroscope

D A thermoluminescent chamber

4 A radioactive substance loses 60% of its original radioactive material after 6750 years. What is the half-life of the substance?

A 9122 years

B 5114 years

C 5625 years

D 6000 years

5 In an electric field, the least deflected radiation is:

A an alpha particle (α).

B a positron (β^+).

C an electron (β^-).

D a gamma ray (γ).

6 A helium nucleus is also known as what type of particle?

7 Identify the daughter nuclide when cobalt-60 undergoes β^- decay.

8 An antineutrino always accompanies what type of decay?

9 List alpha, beta and gamma radiation in order of increasing penetrating ability.

10 What numbers must always balance after an isotope transmutes?

11 Polonium-218 undergoes alpha decay then beta decay. Write the two decay equations for these two stages of the decay series.

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12 A 400 g sample of calcium-49 undergoes β^- decay. After 18 minutes, only 90 g of the original radioactive atoms remain. Determine the half-life of calcium-49.

13 Determine the decay constant of a substance that has a half-life of 1700 s.

14 Explain how an unstable nuclide can become stable through a series of decays. In your response, outline how you can predict what type of radioactive decay a nuclide will undertake in order to become stable.

15 The table below shows the count rate of a radioactive substance over time.

Time (h)	Count rate (Bq)
0	15 000
2	11 023
4	8 100
5	6 944
8	4 374
10	3 215
13	2 025
15	1 488

a Label the axes and plot the information on graph paper.

b What is the approximate half-life of this radioisotope?

16 The amount of carbon-14 can be measured in a dead organism to determine how long ago it lived. This is called radioactive dating. The half-life of carbon-14 is 5730 years, and there are approximately $1:10^{12}$ atoms of carbon-14 to other carbon isotopes. Using this information, explain how the age of a fossil can be determined.

8 NUCLEAR ENERGY AND MASS DEFECT

Introduction

The mushroom cloud that accompanies a nuclear explosion illustrates the enormity of the energy released in a nuclear reaction. Harnessing this energy may provide the answer to the world's increasing energy needs.

In this chapter, Einstein's mass–energy equivalence relationship is explained and applied to measure how much energy is released in nuclear reactions.

Stimulus questions

- Should we be using nuclear power stations for Australia's energy needs?
- How did the splitting of the atom lead to the end of World War II?

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8.1 The energy within the nucleus

Enormous amounts of energy can be produced from atomic nuclei. Radioactive decay products are more energetic than emissions from the atomic-level electron transitions. As such, they can be used to enhance the scope of medical diagnosis and treatment. **Nucleons** (protons and neutrons) are very strongly bound together in the nucleus via the strong nuclear force. Rearrangements of these nucleons by splitting the atom (**fission**) or by adding nucleons together (**fusion**) can release energy. Although each fission or fusion event releases tiny amounts of energy, these amounts are far greater than the energy per atom released in the chemical reactions that take place in traditional methods of obtaining energy, such as the burning of fossil fuels. The difference in energy is typically of the order of 1–10 billion times more energetic. Fission and fusion release enormous amounts of energy due to the significant number of nucleons involved in the reactions multiplied by the energy released per event. The use of nuclear energy for baseload power remains controversial, due to the negative effects on human health from radioactive waste, as well as when things go wrong, such as the melting of the three Fukushima Daiichi reactors following a tsunami that disabled both the power supply and the cooling at the plant on 11 March of 2011, and the explosion of Reactor 4 at Chernobyl on 26 April 1986.

nucleon
a proton or neutron; a particle that makes up the nucleus of an atom

fission
the process by which heavy nuclei ($Z > 56$) separate into fragments, with the release of energy; typically, fission fragments have quite different masses

fusion
the process by which nucleons join to form a new nucleus. Nucleosynthesis is the set of fusion reactions that lead from nucleons to a variety of nuclides. This occurs for light elements ($Z < 56$) and energy is released

The four fundamental forces

There are four fundamental forces identified by physicists that cannot be reduced to more basic interactions: the **gravitational**, **electromagnetic**, **strong nuclear** and **weak nuclear** forces. The two nuclear forces are described as acting at very short range. The strong nuclear force has the greatest effect on maintaining nucleons within the nucleus, while the weak nuclear force, which acts within nucleons, is responsible for radioactive decay.

gravitational force
the manifestation of Newton's universal law of gravitation; a force of attraction acting between every mass throughout the universe

electromagnetic force
the combined electrical and magnetic force acting between charged particles; the force is attractive for unlike charges, and repulsive for like charges

TABLE 8.1.1 Comparison of the four fundamental forces within a nucleus

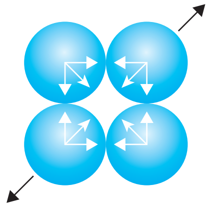
	GRAVITATIONAL FORCE	WEAK NUCLEAR FORCE	ELECTROMAGNETIC FORCE	STRONG NUCLEAR FORCE
Relative magnitude	1	10^{32}	10^{36}	10^{40}
Range (m)	Infinite	10^{-18} or 1 attometre, 1 am	Infinite	10^{-15} or 1 femtometre, 1 fm

What holds an atomic nucleus together?

Protons have a positive charge and, since like charges repel, the protons within the nucleus repel each other with an electrostatic force. The electrostatic force becomes relatively large when the protons are close together, as they are within an atom. In the nucleus, protons come within about 2×10^{-15} m (2 femtometres, 2 fm) of each other. The electrostatic force of repulsion acting between a pair of protons is about 60 N when they are at their closest. Protons have mass and, according to the universal law of gravitation, a gravitational force exists causing them to attract each other. Although one might think that this gravitational force holds the nucleus together, the gravitational force acting between protons is miniscule, even when they are 2 fm apart – it is too small by a factor of 10^{36}.

strong nuclear force
the force required to hold nucleons together, especially to overcome the electrostatic force of repulsion between protons

weak nuclear force
one of the four fundamental forces; acts between subatomic particles (leptons) and is responsible for beta decay



There must be forces between nucleons pulling them together. Gravitational forces are far too small.

FIGURE 8.1.1 The strong nuclear force acts to bind nucleons together, acting against the force of electrostatic repulsion. Gravitational force, though present, is negligible.

The force that keeps nucleons together is the strong nuclear force. In a helium-4 nucleus, for example, the protons and neutrons are bound together by the strong nuclear force that overcomes the repulsion due to the electrostatic force.

The electron-volt, eV

The energy equivalent of nucleon mass is very small – too small to represent conveniently in joules. As a consequence, a different energy unit is used, making the numbers simpler to work with. This energy unit is the **electron-volt, eV**. One electron-volt is equivalent to the energy that an electron gains when it moves through a potential difference of one volt. Thus, 1 eV is equivalent to 1.602×10^{-19} J. Nuclear energies are often in the range of thousands ($\times 10^3$) of eV (keV), millions ($\times 10^6$) of eV (MeV) or billions ($\times 10^9$) of eV (GeV).

electron-volt, eV
a small energy unit, equivalent to 1.60×10^{-19} joules

nuclear binding energy
energy needed to disassemble a nucleus into its component nucleons; measure of stability of a nuclide

mass defect, Δm
the difference in the mass of an atom and the mass of its constituent parts, as expressed in Einstein's mass–energy equation: $\Delta E = \Delta mc^2$

Nuclear binding energy

The binding energy per nucleon governs stability. The higher the binding energy per nucleon the more stable the nuclide. Nuclei are made from protons and neutrons. The energy that would be needed to disassemble a nucleus into its component nucleons is known as the **nuclear binding energy**. Each nucleon, on its own, has a rest mass; however, when nucleons are brought together to form a nucleus, the mass of the nucleus is slightly less than the sum of all the individual nucleons. The difference, Δm, between the sum of the individual masses and the mass of the nucleus into which they are combined is called the **mass defect**. The mass defect is a measure of the energy, E, needed to bind all the parts of a nucleus together. Einstein's mass–energy equation is a quantitative statement of this effect:

$$\Delta E = \Delta mc^2$$

where c = the speed of light in a vacuum, 3.00×10^8 m s^{-1}.

Some of the mass of the individual nucleons appears as the binding energy of the nucleus. In this sense, it is best to consider mass and energy as equivalent and interchangeable; that is, mass $\Leftrightarrow$ energy.

It has been observed that in any nuclear event – radioactive decay, nuclear reaction, fusion and fission – there is a loss of mass. This mass defect appears as energy in amounts predicted by Einstein's mass–energy equation.

Nucleons may have their masses reported in different ways: in kilogram (kg), in unified mass units (u) and energy (MeV).

KEY FORMULA

Einstein's mass–energy equation

$\Delta E = \Delta mc^2$

Where:

c = the speed of light, 3.00×10^8 m s^{-1}

TABLE 8.1.2 Table of rest masses of nucleons, in kilograms and unified atomic mass units

	MASS (kg)	MASS (u)
Proton	1.67208×10^{-27}	1.007 28
Neutron	1.67438×10^{-27}	1.008 66
Electron	9.11×10^{-31}	0.000 55

The unified atomic mass unit, u, has a value of = 1.66×10^{-27} kg and energy equivalent of 931.5 MeV.

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WORKED EXAMPLE 8.1.1

For an alpha particle, calculate the:

a mass defect

b nuclear binding energy

c binding energy per nucleon.

(An alpha particle, α, is a $^{4}_{2}He$ nucleus; it has 2 protons and 2 neutrons and no electrons.)
Use the mass values provided below:

Unified atomic mass unit, u = 1.66×10^{-27} kg
Rest mass of proton, $m_p = 1.00728$ u or 1.67208×10^{-27} kg
Rest mass of neutron, $m_n = 1.00866$ u or 1.67438×10^{-27} kg
Rest mass of alpha particle, $m_\alpha = 4.00153$ u or 6.64254×10^{-27} kg

ANSWERS

a To calculate the mass defect, determine the combined mass of the individual components that make up the nucleus, and then subtract the rest mass of the complete particle.
Mass of combined components:

2 × mass of proton	$2 \times 1.67208 \times 10^{-27}$ kg
+ 2 × mass of neutron	$2 \times 1.67438 \times 10^{-27}$ kg
	$= 6.692.92 \times 10^{-27}$ kg
Rest mass of alpha particle	6.64254×10^{-27} kg
Mass defect, Δm	6.69292×10^{-27} kg $- 6.64254 \times 10^{-27}$ kg

$\Delta m = 0.05038 \times 10^{-27}$ kg
$\Delta m = 0.03035$ u

b To calculate the nuclear binding energy, use Einstein's mass–energy equation, $\Delta E = \Delta mc^2$, where c = the speed of light, 3.00×10^8 m s^{-1}.
$E = \Delta mc^2 = 0.05038 \times 10^{-27}$ kg $\times (3.00 \times 10^8 \text{ m s}^{-1})^2$
$E = 4.5349 \times 10^{-12}$ joules
$E = 28.339$ MeV (where 1 eV = 1.60×10^{-19} J, hence 1 MeV = 1.60×10^{-13} J)

c To calculate the binding energy per nucleon, simply divide the nuclear binding energy by the number of nucleons (protons and neutrons).
$E = 4.5349 \times 10^{-12}/4 = 1.1337 \times 10^{-12}$ joules per nucleon, or
$E = 28.339$ MeV/4 = 7.084 MeV per nucleon

The binding energy per nucleon is shown graphically in Figure 8.1.2 (page 152) for nuclides up to uranium, the heaviest naturally occurring element. The binding energy per nucleon is a significant quantity when determining the stability of nuclides. The greater the binding energy per nucleon, the harder it is to pull the nucleus apart and the more stable the nuclide. Iron-56 is at the very top of the curve and is the most stable of the nuclides. Unstable elements with greater mass than iron release energy when they undergo fission (break apart); elements with a lesser mass than iron release energy when undergoing fusion (being fused or forced together). The binding energy per nucleon governs stability. The higher the binding energy per nucleon, the more stable the nuclide. Fusion is favoured for light nuclides ($Z < 56$). Fission is favoured for heavy nuclides ($Z > 56$).

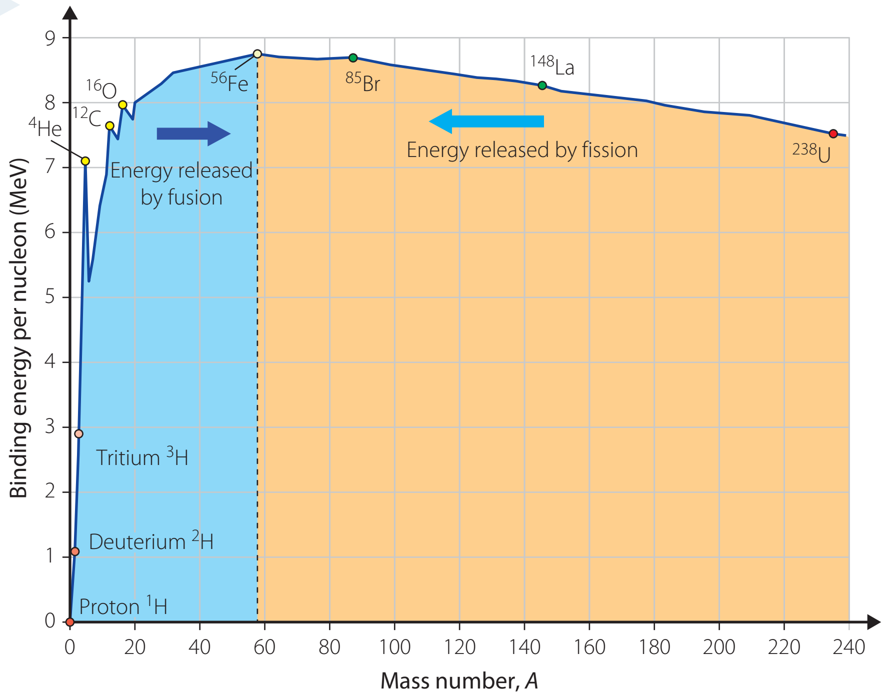

FIGURE 8.1.2 Graph of the binding energy per nucleon as a function of mass number, *A*

Table 8.1.3 shows the total binding energy for nuclides as well as the binding energy per nucleon. Consider He-4, which has a total binding energy of 28.29 MeV. It has 4 nucleons, so its binding energy per nucleon is 7.07 MeV per nucleon.

TABLE 8.1.3 Nuclear binding energy and binding energy per nucleon for some nuclides

ELEMENT	BINDING ENERGY (MeV)	BINDING ENERGY PER NUCLEON (MeV)
Deuterium (hydrogen-2)	2.23	1.12
Helium-4	28.29	7.07
Lithium-7	40.15	5.74
Beryllium-9	58.13	6.46
Iron-56	492.24	8.79
Silver-107	915.23	8.55
Iodine-127	1072.53	8.45
Lead-206	1622.27	7.88
Polonium-210	1645.16	7.83
Uranium-235	1783.80	7.59
Uranium-238	1801.63	7.57

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SECTION REVIEW 8.1

REMEMBERING

1 Define each of the terms in the equation $\Delta E = \Delta mc^2$.

2 Define the following terms.

a Electromagnetic force

b Strong nuclear force

c Gravitational force

d Weak nuclear force

e Nuclear binding energy

UNDERSTANDING

3 Draw a table to show the relative magnitudes and ranges of the four fundamental forces.

APPLYING

4 Calculate a the mass defect, b nuclear binding energy and c binding energy per nucleon of a helium-3 isotope ($^3_2$He). Include the mass of the two electrons.

Use the mass values provided below:

Unified atomic mass unit, $u = 1.660\,539 \times 10^{-27}$ kg

Rest mass of proton, $m_p = 1.007\,28$ u or $1.672\,08 \times 10^{-27}$ kg

Rest mass of neutron, $m_n = 1.008\,66$ u or $1.674\,38 \times 10^{-27}$ kg

Rest mass of electron, $m_e = 9.11 \times 10^{-31}$ kg

Rest mass of He-3 = 3.016 03 u or $5.006\,61 \times 10^{-27}$ kg

5 Calculate a the mass defect, b nuclear binding energy and c binding energy per nucleon of a $^{14}_7$N, nitrogen-14 isotope. Include the mass of the seven electrons.

Use the mass values provided below:

Unified atomic mass unit, $u = 1.660\,539 \times 10^{-27}$ kg

Rest mass of proton, $m_p = 1.007\,28$ u or $1.672\,08 \times 10^{-27}$ kg

Rest mass of neutron, $m_n = 1.008\,66$ u or $1.674\,38 \times 10^{-27}$ kg

Rest mass of electron, $m_e = 9.11 \times 10^{-31}$ kg

Rest mass of N-14 = 14.0067 u or 2.3251×10^{-26} kg

8.2 Transmutations

Transmutation, the process of transforming one element (or nuclide) into another by radioactive decay or nuclear bombardment, may occur either naturally or artificially. **Natural transmutation** occurs through the continual and spontaneous process of radioactive decay. In contrast, **artificial transmutation** may be synthetically generated by bombarding a nucleus with a neutron or other small nucleus, such as an alpha particle.

The discovery of the neutron enabled scientists to explore the behaviour of larger atomic nuclei. As they are neutral, neutrons are not repelled by the target nucleus and can be absorbed into the nucleus of the target atom. This makes neutrons very useful as a form of bombarding radiation, and they are used in many experiments to transmute a number of nuclides artificially.

natural transmutation the conversion of one chemical element or isotope into another through natural radioactive decay

artificial transmutation the conversion of one chemical element or isotope into another through a synthetic process, typically through bombarding a nucleus with slow (thermal) neutrons to cause fission events

Artificial transmutation

slow (thermal) neutron neutron with kinetic energy of about 0.1–20 keV

In artificial transmutations, the target nucleus is bombarded with an incoming **slow (thermal) neutron**. The nucleus of the atom effectively 'captures' the neutron, becoming unstable and subsequently emitting radioactive decay. Recall that Rutherford was the first to use radioactivity to produce new nuclides. He bombarded nitrogen-14 with alpha particles, analysed the result and found that oxygen and hydrogen were formed. The reaction proceeded as follows.

Nitrogen nuclei absorb helium nuclei and form a composite, unstable nuclide, denoted by an asterisk:

$$^{14}_{7}N + ^{4}_{2}He \rightarrow ^{18}_{9}F^{*}$$

The composite nuclide decays to a more stable state:

$$^{18}_{9}F \rightarrow ^{17}_{8}O + ^{1}_{1}H$$

SECTION REVIEW 8.2

REMEMBERING

1 Identify the term for each the definition:

- **a** The conversion of one chemical element or isotope into another through natural radioactive decay
- **b** The conversion of one chemical element or isotope into another through a synthetic process, typically through bombarding a nucleus with slow (thermal) neutrons to cause fission events

APPLYING

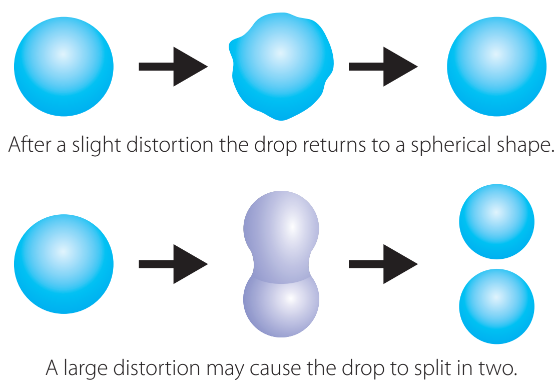
2 Insert the correct values for A and Z in the transmutation equation for fluorine:

$$^{14}_{\square}N + ^{4}_{2}He \longrightarrow ^{\square}_{\square}F^{*}$$

8.3 Nuclear fission

Nuclear fission is the process by which a nucleus splits into two or more fragments. In 1938, while trying to explain others' findings, Lise Meitner (1978–68) and Otto Frisch (1904–79) determined that a uranium nucleus had split in two. This was an unexpected result at the time. (In general, the fragments are rarely the same size, so it is incorrect to say that the atom 'splits in half'). In the process, neutrons are released and energy, initially stored as nuclear binding energy, is released. Nuclear fission may occur as natural radioactive decay, or may be induced through an artificial transmutation, triggered by the absorption of a neutron. When a nucleus absorbs a slow neutron, it becomes less stable. Bombarding uranium nuclei with neutrons leads to the formation of a transuranic element, or the splitting of the unstable uranium into two nuclei of intermediate mass.

FIGURE 8.3.1 Liquid-drop model of fission. A nucleus that absorbs an additional neutron undergoes large distortions and splits into two (or more) smaller fragments.



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Irène Joliot-Curie (1897–1956), daughter of Marie Curie (1867–1934), was the first to identify the products of nuclear fission. Enrico Fermi (1901–1954) was the first to control nuclear fission. On 2 December 1942, in a squash court under the stadium at the University of Chicago, the first self-sustaining nuclear reactor began operation. Five days later, the Japanese entered World War II by attacking Pearl Harbour, and their involvement eventually led to the atomic bomb being dropped on Hiroshima and Nagasaki in 1945. Thus began the nuclear age.

Some common nuclear fission reactions can be expressed in equation form, as below. Note that the sum of the nucleon numbers (A) and atomic numbers (Z) on either side of the equation are equal. Further, each equation liberates (frees) additional neutrons – each of which may go on to induce another nuclear fission reaction.

8.3.1 Nuclear fission

8.3.2 Nuclear fission and fusion

8.3.3 Irene Joliot-Curie

Examples of neutron-induced nuclear fission equations

Fission occurs when neutron absorption in the nuclei of elements such as uranium and plutonium causes splitting into two, usually unequal, fragments. Neutrons are released and can be controlled (to sustain) or deliberately uncontrolled (to magnify) the release of energy.

$$^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{92}_{36}\text{Kr} + ^{141}_{56}\text{Ba} + 3\,^{1}_{0}\text{n} + \text{energy}$$
$$^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{90}_{38}\text{Sr} + ^{143}_{54}\text{Xe} + 3\,^{1}_{0}\text{n} + \text{energy}$$
$$^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{144}_{55}\text{Cs} + ^{90}_{37}\text{Rb} + 2\,^{1}_{0}\text{n} + \text{energy}$$

Fission fragments

Nuclides that are capable of undergoing nuclear fission after absorbing a neutron are said to be **fissile**. Fissile nuclides are very uncommon. Uranium-235 and plutonium-239 are readily fissile and undergo nuclear fission with low-energy 'slow' neutrons (in the range 0.02 eV to several keV). Uranium-238 is only slightly fissile; it requires a very high energy neutron, in excess of 1 MeV, to induce fission. Thorium-232 can absorb a neutron and undergo beta decay to become uranium-233, which is also fissile.

fissile
capable of being split or divided, e.g. by undergoing fission; U-235, U-238, U-233, Pu-239

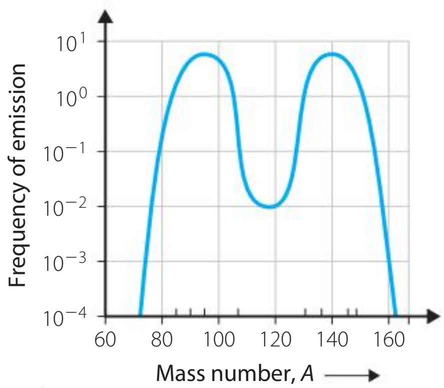

FIGURE 8.3.2 The most likely fission fragments from U-235 have atomic mass numbers around 95 and 140. The vertical scale is logarithmic – equal distances along the axis represent equal ratios, in this case × 10.

A uranium-235 nucleus may split in many different ways. More than 40 different pairs of fission fragments of uranium-235 have been found. In the nuclear fission equation below, krypton-92 and barium-141 are known as the **fission fragments** (or fission products).

$$^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{92}_{36}\text{Kr} + ^{141}_{56}\text{Ba} + 3\,^{1}_{0}\text{n} + \text{energy}$$

fission fragment
nucleus produced as a result of fission; fission product

Radiochemical analysis shows that most fission fragments have an atomic mass number between 72 and 158 and an atomic number between 30 and 63. The splitting of a fissile nucleus into two equal parts is rare – about 0.01%. Other common fission fragment pairs produced in the fission of uranium-235 include xenon-140 and strontium-94, and tin-132 and molybdenum-101. Some of these fission fragment nuclei can themselves be struck by, and absorb, a neutron, forming a different radionuclide that may then radioactively decay.

WORKED EXAMPLE 8.3.1

A thermal neutron, mass 1.01 u, causes fission of U-235 (235.04 u). The fission fragments and their masses, in unified mass units, are Rb-93 (92.92 u) and Cs-141(140.92 u).

a How many fast neutrons are released in this fission event?

b Write the nuclear fission reaction using the correct nuclide and nucleon symbols.

c Calculate the mass defect in this event, giving the answer in:

  i unified mass units

  ii kilograms.

d How much energy is released? Give your answer in joules.

ANSWERS

a Nucleon number is conserved:
Total nucleons before = 1 + 235 = 236
Total nucleons after = 93 + 141 + x
$x + 234 = 236$
$x = 2$
Two neutrons were released.

b ${}^{1}_{0}\text{n} + {}^{235}_{92}\text{U} \rightarrow {}^{93}_{37}\text{Rb} + {}^{141}_{55}\text{Cs} + 2\,{}^{1}_{0}\text{n}$

c Mass defect = (1.01 + 235.04) − (92.92 + 140.92 + 2 × 1.01) u
Mass defect = 0.19 u
$= 0.19\,\text{u} \times 1.66 \times 10^{-27}\,\text{kg}\,\text{u}^{-1}$
Mass defect = 3.15×10^{-28} kg

d Calculate the energy released:
$\Delta E = \Delta mc^2$
$= 3.15 \times 10^{-28}\,\text{kg} \times (3.00 \times 10^{8}\,\text{m}\,\text{s}^{-1})^2$
$\Delta E = 2.84 \times 10^{-11}\,\text{J}$

SECTION REVIEW 8.3

REMEMBERING

1 Write the symbol for the element uranium, including the notation for mass number and atomic number.

2 Define:

  a fission.

  b fission fragment.

UNDERSTANDING

3 Complete the missing mass and atomic numbers and element symbol in the nuclear fission equation below:

$${}^{235}_{\square}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{\square}_{36}\text{Kr} + {}^{141}_{56}\square + 3\,{}^{1}_{0}\text{n} + \text{energy}$$

APPLYING

4 In a nuclear reaction that starts with uranium, a thermal neutron, mass 1.01 u, causes fission of U-233 (233.044 u). The fission fragments and their masses, in unified mass units, are Mo-104 (103.91 u), Sn-126 (125.91 u) and four neutrons.

  a Write the nuclear fission reaction using the correct nuclide and nucleon symbols.

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- **b** Identify the mass defect in this event in:
  - **i** unified mass units
  - **ii** kilograms.
- **c** How much energy is released? Give your answer in joules.

5 In a fast breeder reactor, a fast neutron, mass 1.01 u, causes fission of Pu-239 (239.05 u). One of the two fission fragments is Tc-104 (103.91 u); three neutrons are also released. The mass defect in this event is 0.19 u.

- **a** What is the nuclide symbol for the second fission fragment?
- **b** Write the nuclear fission reaction using correct nuclide and nucleon symbols.
- **c** Determine the mass defect for the reaction, giving the answer in kilograms.
- **d** How much energy is released? Give your answer in joules.

8.4 Fission chain reactions

Uranium-235 can absorb a slow neutron or thermal neutron that has about 5–10 keV of energy. The neutron is absorbed in the uranium nucleus and forms a composite, unstable nucleus that then splits into smaller fragments, each with lower atomic mass than the uranium-235. On average, between two and three neutrons are also released. The neutrons released from the fission of uranium-235 are 'fast' neutrons and do not usually get absorbed by uranium-235 nuclei unless they are slowed down by a moderator. This is a natural process that rarely amounts to anything substantial. However, if conditions are right, the process can be used to harness the energy of the mass defect, which is about 200 MeV per fission event.

A chain reaction occurs when more than one of the neutrons released from the initial fission event causes new events to occur. In Figure 8.4.1, each fission event produces two or three neutrons, some of which go on to cause new fission events. This rapidly multiplies to a significant number of fission events, and, unless this is carefully controlled, a runaway explosion will occur.

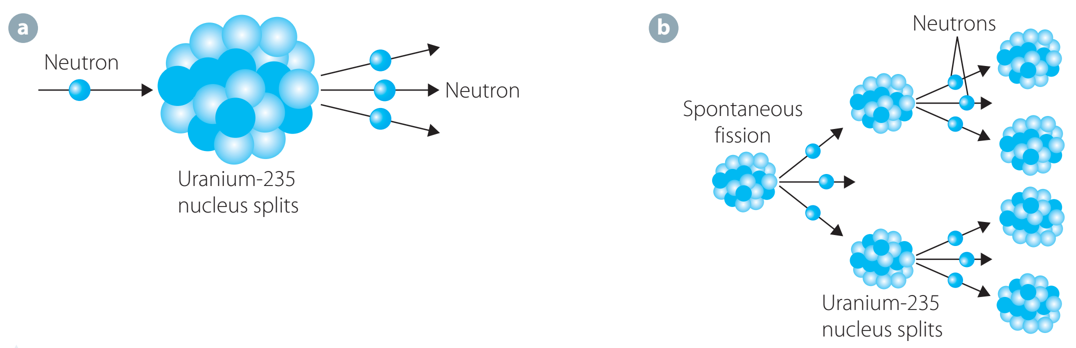

FIGURE 8.4.1 A nuclear fission chain reaction. (a) A slow neutron causes a uranium-235 nucleus to become unstable and split, releasing three fast neutrons in addition to energy. (b) A chain reaction occurs, if, for example, two of the three released neutrons induce nuclear fissions in other uranium nuclei. Consequently, vast amounts of energy are released.

Controlled fission is used in nuclear power stations. Thermal nuclear power stations use slow (thermal) neutrons to release energy. The purpose of a nuclear power reactor is to release nuclear energy at a controllable rate. The reactor does not generate electricity directly; rather, the heat generated produces steam that powers the turbines and generators of the electricity production plant.

Controlled chain reaction

The chain reaction can be controlled for nuclear power generation. One neutron produces one fission neutron in a **controlled chain reaction**. If more than one neutron is produced on average, then a runaway reaction occurs. If the average number of neutrons produced is less than one, then the reaction dies away. It is quite difficult to establish and maintain a chain reaction, but this is achieved with the use of control rods to absorb excess neutrons. Control rods made of substances that readily absorb neutrons, such as cadmium or boron steel, are inserted into the reactor to reduce the number of neutrons produced by each reaction to one only.

controlled chain reaction
a chain of nuclear reactions that are controlled to limit the rate at which they occur. In steady state (reaction rate held constant), an average of one neutron from each reaction goes on to cause another reaction. This is the case for a nuclear power reactor running at constant power output

enrichment
a process of separating out U-235 from a sample and adding it to another sample, increasing the proportion of U-235 in natural uranium

uncontrolled chain reaction
a chain of nuclear reactions that are not controlled. Usually this means a reaction rate that increases rapidly. For this to occur the average number of neutrons from each reaction that go on to cause more reactions is greater than one

moderator
light atoms in a nuclear reactor that slow down fast neutrons to thermal speeds, in order to increase the likelihood of further fission events; often heavy water is used

Enrichment

For fission to occur in uranium-235 the initial neutron must be a thermal neutron. The neutrons produced in fission events are 'fast' neutrons. The probability of these neutrons causing new fission events in uranium-235 is very small. It is more likely that they will be captured by uranium-238 or some other neutron poison that was produced by an earlier fission event. These neutron poisons hold onto the neutrons and emit α, β or γ radiation.

In order to ensure sustained fission, the proportion of uranium-235 must be increased. This **enrichment** process is achieved by separating uranium-235 out of naturally occurring uranium ore. This separated amount is then put back into a quantity of naturally occurring uranium. This increases, or enriches, the proportion of uranium-235 in the quantity. It is a complex and expensive process. In order to guarantee an **uncontrolled chain reaction**, enrichment may be as high as 97% uranium-235. For a controlled reaction, 1–4% enrichment is sufficient.

Moderator

In order to reduce the energy of the neutrons produced by fission events, a moderator is used. The **moderator** is a material with nuclides that have slightly larger masses than the neutron – hydrogen ($^{1}_{1}H$), deuterium ($^{2}_{1}H$) and tritium ($^{3}_{1}H$), for example. Neutrons share their energy with these nuclides through multiple collisions. The neutrons rapidly lose energy, which increases their probability of entering a uranium-235 nucleus and causing fission.

Reactor vessel

In a reactor, a controlled chain reaction will not proceed unless most of the neutrons available can be used. Apart from absorption in neutron poisons, some neutrons will escape from the fuel. This is because the absorption of a neutron and subsequent fission occurs only when there is a head-on collision between a nucleus and a neutron. The reactor vessel is therefore designed to have the right surface area to volume ratio, and is made of a high nucleon number material, so that the neutrons are reflected back into the sample.

Coolant

As a large amount of energy is produced in each fission reaction, and this is carried as kinetic energy by the fission products, the temperature of the reactor would increase unless a coolant was used. The coolant material is used to absorb and then transfer this heat so that it can be used for energy purposes outside of the reactor itself.

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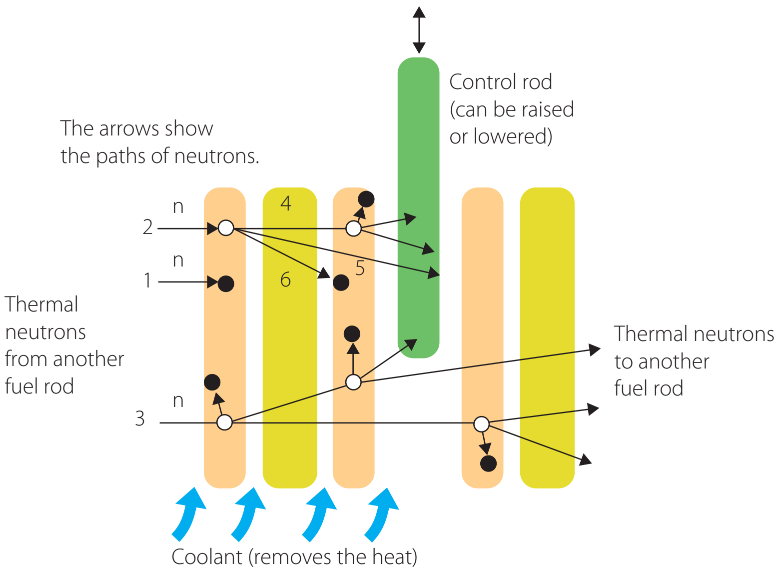
Control rods

On average, the number of neutrons produced by fission events must be equal to the number of fission-producing neutrons in order to sustain a nuclear reaction. Sometimes the reaction threatens to run away, so control rods containing neutron poisons, such as boron-10, are moved into the fuel to lower the number of neutrons in the sample. The control rods are removed when the chain reaction starts to produce too few neutrons.



	Isotope	Natural	Enriched	Neutron capture →
○	^{235}U	0.7%	2.3%	fission
●	^{238}U	99.3%	97.7%	absorption

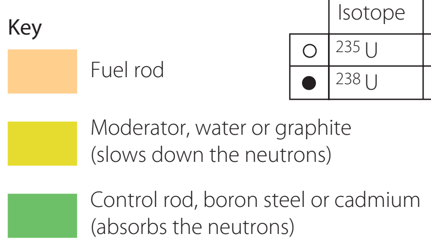


FIGURE 8.4.2 Controlling a chain reaction in a nuclear reactor. Some neutrons are numbered to explain the process. Neutron 1 is captured by a fuel rod, neutrons 2 and 3 cause nuclear fission, releasing more neutrons, neutron 4 causes further fission, neutron 5 is absorbed by a control rod and neutron 6 is absorbed by a fuel rod.

SCIENCE AS A HUMAN ENDEAVOUR

The debate continues regarding the relative merits and drawbacks of nuclear- and coal-powered electricity generation. Nuclear reactors produce far more energy per kilogram of fuel than the burning of fossil fuels. In normal operation, nuclear reactors release no radioactive materials or other chemicals, such as the greenhouse gas carbon dioxide. Coal-fired power stations release pollutants such as fly ash, oxides of carbon, sulfur and nitrogen along with radioactive chemicals. In both fuel consumption and waste production, a nuclear power station is far more fuel efficient and far less wasteful, including unintended emissions, than a coal-fired power station. Understanding of the efficiency of each source, as well as the risks involved, supports governments in effective decision making about safe, cost-effective and sustainable energy production.

Consider whether Australia should generate power using nuclear fission. To do this effectively, you will need to determine criteria for evaluation, develop a decision-making matrix, perform research and justify a position. Determine up to six criteria for evaluation, such as the relative abundance; i.e. number of years of access to the fuel source, or the cost (both initial start-up cost and the annual running cost, per MWh), as well as public safety. Conduct research to determine the energy efficiency of coal-fired and nuclear-powered electricity plants, as well as current solutions to storage of nuclear waste and the problems associated with radioactive waste disposal. You may also investigate the prevalence of nuclear- and coal-powered electricity generation across several nations (e.g. Australia, France and Japan) to see how much energy is generated from each of these sources.

SECTION REVIEW 8.4

REMEMBERING

1 Construct a table to summarise the role of the moderator, control rods, reactor vessel and coolant elements of a nuclear power reactor.

2 Define 'slow (thermal) neutron'.

UNDERSTANDING

3 Explain how the control rods can be used to regulate the rate of reactions within a reactor.

APPLYING

4 Explain why a nuclear chain reaction can become explosive so quickly. Use a diagram and mathematical model to assist your explanation.

REFLECTING

5 Construct a table to list three arguments for and three arguments against the use of nuclear power generation in Australia.

8.5 Nuclear fusion

Fusion is the joining together of two smaller nuclides to form a new nucleus with a greater atomic number. The new composite nucleus is more stable because its binding energy per nucleon is greater. This is more likely to occur for nuclides that have an atomic number $Z < 56$. Fusion is difficult to achieve as a lot of work is required to fuse nuclei; however, when they do fuse, a lot of additional energy is released. Nuclear fusion reactions occur within the core of our Sun, which fuses 620 million tons of hydrogen each second.

Some common nuclear fusion reactions can be expressed in equation form, as below. Note that the sum of the nucleon numbers (A) and atomic numbers (Z) on either side of the equation are equal. Further, each equation releases energy, as a result of Einstein's mass–energy equivalence relationship.

Examples of nuclear fusion equations

For example, the fusion of two hydrogen isotopes forms helium, with an excess neutron and the accompanying release of energy.

$$^{2}_{1}\text{H} + ^{2}_{1}\text{H} \rightarrow ^{3}_{2}\text{He} + ^{1}_{0}\text{n} + \text{energy}$$
$$^{2}_{1}\text{H} + ^{3}_{1}\text{H} \rightarrow ^{4}_{2}\text{He} + ^{1}_{0}\text{n} + \text{energy}$$

SECTION REVIEW 8.5

REMEMBERING

1 Define 'nuclear fusion'.

2 What type of nuclear reaction occurs within the Sun – fusion or fission?

APPLYING

3 Complete the missing values in the nuclear fusion reaction below:

$$^{\square}_{1}\text{H} + ^{2}_{\square}\text{H} \rightarrow ^{3}_{2}\text{He} + ^{1}_{0}\text{n} + \text{energy}$$

4 Contrast nuclear fusion with nuclear fission.

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8.6 Nuclear safety

Nuclear energy production starts with the mining of radioactive materials, which are usually found underground and out of the way of human interactions. Nuclear power stations concentrate energy production in a few locations and are potential targets for militant individuals, organisations and nations. It can take thousands of years before much of the waste from spent fuels is considered safe. Also, nuclear weapons and nuclear deterrents can and have been used by nations prepared to advance their causes or protect their dominant positions in the world.

Nuclear waste

Nuclear energy production by fission reactors produces radioactive waste. The disposal of radioactive waste is one of the major problems faced by the nuclear power industry. Table 8.6.1 provides a comparison of waste produced by nuclear reactors and coal-fired power stations.

TABLE 8.6.1 Comparative waste produced by nuclear and coal-fired electrical power plants

TYPE OF POWER	CAPACITY	WASTE
Nuclear power station	1000 MW	25 tonnes of radioactive material
Coal-fired power station	1000 MW	Millions of tonnes of carbon dioxide and sulfur dioxide

FIGURE 8.6.1 The waste from a nuclear fission reactor has to be stockpiled, shielded and cooled for periods of thousands of years until safe, yet, when used correctly, nuclear-powered electricity generation is more efficient and less polluting than that from coal-fired power stations.

Radioactive waste products are classified into three categories: high, medium and low level. High-level wastes are radioactive and continue to release significant amounts of energy during the decay process. This energy may be in the form of radioactivity or heat and systems must be in place to reduce harmful effects. Table 8.6.2 (page 162) shows a classification of radioactive waste.

8.6.1 Managing nuclear waste

TABLE 8.6.2 Classification of radioactive waste

WASTE CATEGORY	DESCRIPTION	STORAGE
High level	Used fuel rods, highly radioactive. It takes about 1000 years to return to the initial radioactive level of the uranium ore, and about 5 million years to be rendered harmless	Must be stored in shielded containers to prevent radiation as well as cooled to stop overheating
Medium or intermediate level	Other reactor components in the reactor core, such as fuel containers, gauges, pipes	Requires shielding, but not cooling
Low level	Used protective clothing; water from showers and water from cleaning protective gear	Can be released to the environment after being diluted

SCIENCE AS A HUMAN ENDEAVOUR

Controversial issues, such as nuclear-fission-powered electricity production, elicit opposing and often emotional statements in the media. Thus, it is important to consider the suitability of sources of information in terms of bias, relevance and accuracy. A model for evaluating the suitability of sources of information is the five-point model of Authority, Accuracy, Objectivity, Currency and Coverage.

1 Authority – refers to the author's status and credibility. Authority is essentially some background information on who wrote or produced the article.

2 Accuracy – a brief comparison to the other articles and information identified. If the information in an article is counter to all others, then it may be inaccurate.

3 Objectivity – refers to bias. Factual information that explains subject matter 'scientifically' using plain, non-emotive language is usually objective. This may also link back to the author – consider whether they are trying to sell something or persuade you, or whether there are advertisements accompanying their article. Read with scepticism.

4 Currency – refers to the date of publication. Older articles are not necessarily inappropriate; however, science and technology move at a rapid pace. Usually more recent articles contain more up-to-date information.

5 Coverage – an assessment of the relevant factual information in the article.

Using the five-point model for evaluation of sources, perform research into aspects of nuclear safety. You may choose to investigate aspects including air pollution, solid waste generation and storage, water contamination, the contribution to climate change or the impact of mining of natural resources.

INQUIRING FURTHER

Advances in scientists' understanding of the properties of nuclear radiation have influenced medical treatment and imaging.

The Australian Nuclear Science and Technology Organisation (ANSTO) is the home of Australia's largest nuclear reactor. The organisation is recognised for its contributions to nuclear science and technology and it operates one of the world's most modern nuclear research reactors, OPAL. ANSTO plays a critical role in the healthcare of Australians being treated for serious illnesses, such as heart disease and cancer. Nuclear medicines, such as the 10 000 doses produced weekly, can be used diagnostically to identify or therapeutically to treat diseases. Advanced techniques for medical imaging that use specific nuclear isotopes can target vessels, organs and tumours to show their structures and functions in ways that X-rays cannot.

Investigate the role of radioisotopes technetium-99m, sodium iodide-131, chromium-51 and gallium citrate-67 in medical diagnosis and treatment. Alternatively, perform research to determine the use of radiopharmaceuticals to diagnose and treat diseases of the brain, salivary glands, thyroid, lungs, liver, spleen, kidney and gall bladder.

SECTION REVIEW 8.6

REMEMBERING

1 Identify an example from each of the three nuclear waste categories: high level, medium level and low level.

2 Describe the mechanism for the storage of spent nuclear fuel.

REFLECTING

3 Name the different points in the five-point model for the evaluation of sources of information.

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8.7 Solving problems using Einstein's mass–energy equivalence relationship

Recall Einstein's mass–energy equivalence relationship, equating the mass defect with energy via the formula $\Delta E = \Delta mc^2$, where c = the speed of light, $3.00 \times 10^8\,\text{m}\,\text{s}^{-1}$. This relationship may be used to determine the energy released from both nuclear fission and nuclear fusion reactions.

In nuclear fission reactions, the total mass before fission is greater than the total mass after the fission event. The mass difference is the mass that has been converted into energy. This energy is transferred via the fission products. The large daughter nuclei carry most of this energy as kinetic energy. The released neutrons also have kinetic energy. For example, when uranium-235 undergoes fission to produce krypton-92 and barium-141, three neutrons are released:

$$^{1}_{0}\text{n} + {}^{235}_{92}\text{U} \xrightarrow{\text{yields}} {}^{92}_{36}\text{Kr} + {}^{141}_{56}\text{Ba} + 3\,{}^{1}_{0}\text{n}$$

There are 236 nucleons before and after this fission event, yet the mass of the products is less than the sum of the mass of the original neutron and uranium-235 nuclide. This difference is the mass defect.

WORKED EXAMPLE 8.7.1

Calculate the mass defect and the energy released in the nuclear fission reaction:

$$^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{92}_{36}\text{Kr} + {}^{141}_{56}\text{Ba} + 3\,{}^{1}_{0}\text{n} + \text{energy}$$

Use the mass values provided below:

Unified atomic mass unit, $\text{u} = 1.660\,54 \times 10^{-27}\,\text{kg}$
Rest mass of neutron, $m_\text{n} = 1.008\,66\,\text{u}$ or $1.674\,38 \times 10^{-27}\,\text{kg}$
Rest mass U-235 = $235.1727\,\text{u}$ or $3.9039 \times 10^{-25}\,\text{kg}$
Rest mass Kr-92 = $91.9262\,\text{u}$ or $1.5260 \times 10^{-25}\,\text{kg}$
Rest mass Ba-141 = $140.9144\,\text{u}$ or $2.3392 \times 10^{-25}\,\text{kg}$

ANSWER

To calculate the mass defect, determine the combined mass of the reactants, and then subtract the combined mass of the products:

Mass of combined reactants

mass U-235	$3.9039 \times 10^{-25}\,\text{kg}$
+ mass of neutron	$1.674\,38 \times 10^{-27}\,\text{kg}$
	$= 3.920\,64 \times 10^{-25}\,\text{kg}$

Mass of combined products

mass Kr-92	$1.5260 \times 10^{-25}\,\text{kg}$
mass of Ba-141	$2.3392 \times 10^{-25}\,\text{kg}$
+ 3 × mass of neutron	$5.023\,14 \times 10^{-27}\,\text{kg}$
	$= 3.915\,43 \times 10^{-25}\,\text{kg}$

Mass defect, $\Delta m = 3.920\,64 \times 10^{-25}\,\text{kg} - 3.915\,43 \times 10^{-25}\,\text{kg}$

$\Delta m = 0.005\,21 \times 10^{-25}\,\text{kg}$

$\Delta m = 0.313\,86\,\text{u}$

To calculate the energy released, use Einstein's mass–energy equation, $\Delta E = \Delta mc^2$, where c = the speed of light, $3.00 \times 10^8\ \text{m s}^{-1}$.

$E = \Delta mc^2 = 0.00521 \times 10^{-25}\ \text{kg} \times (3.00 \times 10^8\ \text{m s}^{-1})^2$

$E = 4.6890 \times 10^{-11}\ \text{J}$

$E = 293.06\ \text{MeV}$ (where $1\ \text{eV} = 1.60 \times 10^{-19}\ \text{J}$, hence $1\ \text{MeV} = 1.60 \times 10^{-13}\ \text{J}$)

As in nuclear fission reactions, in nuclear fusion reactions the total mass before fusion is greater than the total mass after the fusion event. The mass difference has again been converted into energy. Although it takes a lot of work to force the nuclei together, a lot of energy is released when they do fuse. For example, when two isotopes of hydrogen fuse to form helium, energy is released.

$$^{2}_{1}\text{H} + ^{3}_{1}\text{H} \rightarrow ^{4}_{2}\text{He} + ^{1}_{0}\text{n} + \text{energy}$$

There are five nucleons before and after this fusion event, yet the mass of the products is less than the mass of the original hydrogen isotopes. This difference is the mass defect.

WORKED EXAMPLE 8.7.2

Calculate the mass defect and the energy released in the nuclear fusion reaction:

$^{2}_{1}\text{H} + ^{2}_{1}\text{H} \rightarrow ^{3}_{2}\text{He} + ^{1}_{0}\text{n} + \text{energy}$

Use the mass values provided below:

Unified atomic mass unit, $\text{u} = 1.66 \times 10^{-27}\ \text{kg}$
Rest mass of neutron, $m_n = 1.00866\ \text{u}$ or $1.67438 \times 10^{-27}\ \text{kg}$
Rest mass H-2 = $2.01355\ \text{u}$ or $3.34249 \times 10^{-27}\ \text{kg}$
Rest mass He-3 = $3.01603\ \text{u}$ or $5.00661 \times 10^{-27}\ \text{kg}$

ANSWER

To calculate the mass defect, determine the combined mass of the reactants, and then subtract the combined mass of the products.

Mass of combined reactants:

mass H-2	$3.34249 \times 10^{-27}\ \text{kg}$
+ mass H-2	$3.34249 \times 10^{-27}\ \text{kg}$
	$= 6.68500 \times 10^{-27}\ \text{kg}$

Mass of combined products:

mass He-3	$5.00661 \times 10^{-27}\ \text{kg}$
+ mass neutron	$1.67438 \times 10^{-27}\ \text{kg}$
	$= 6.68099 \times 10^{-27}\ \text{kg}$

Mass defect, $\Delta m = 6.68500 \times 10^{-27}\ \text{kg} - 6.68099 \times 10^{-27}\ \text{kg}$

$\Delta m = 0.00401 \times 10^{-27}\ \text{kg}$

$\Delta m = 0.00242\ \text{u}$

To calculate the energy released, use Einstein's mass–energy equation, $\Delta E = \Delta mc^2$, where c = the speed of light, $3.00 \times 10^8\ \text{m s}^{-1}$.

$E = \Delta mc^2 = 0.00401 \times 10^{-27}\ \text{kg} \times (3.00 \times 10^8\ \text{m s}^{-1})^2$

$E = 3.6090 \times 10^{-13}\ \text{J}$

$E = 2.2556\ \text{MeV}$ (where $1\ \text{eV} = 1.60 \times 10^{-19}\ \text{J}$, hence $1\ \text{MeV} = 1.60 \times 10^{-13}\ \text{J}$)

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Nuclear fusion versus nuclear fission

Fusion reactions release much more energy than fission reactions per kilogram of reactant. We have seen that fusion is favoured for elements up to Fe-56. For lighter elements, the curve of the binding energy per nucleon graph (Figure 8.7.1) is quite steep, which means that any fusion reaction will release a relatively large amount of energy when the new nuclide is formed.

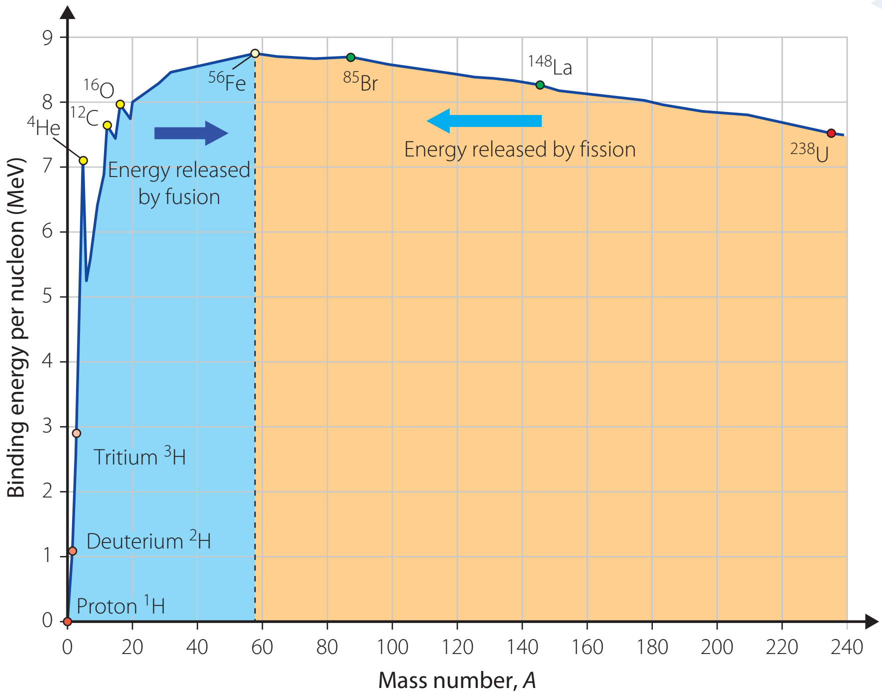

FIGURE 8.7.1 Graph of the binding energy per nucleon as a function of mass number, *A*

For example, Figure 8.7.1 shows that, for tritium, $^{3}_{1}H$, an isotope of hydrogen, the binding energy per nucleon is approximately 2.9 MeV. This is higher than the binding energy per nucleon for the proton (0 MeV) and deuterium, $^{2}_{1}H$, (1.1 MeV). Fusion of a proton with deuterium to produce tritium releases about 1.8 MeV of energy per nucleon. This amounts to the release of approximately 62% of the original binding energy per nucleon.

At the other end of the graph, where fission is favoured over fusion for elements heavier than Fe-56, energy is also released, but comparatively less. The binding energy per nucleon of uranium-235 is approximately 7.6 MeV. For the two most common fission fragments, the binding energy per nucleon is about 8.6 MeV. Taking account of both fission fragments, the difference is approximately 2.0 MeV. For fission, the release of energy per nucleon is about 26% of the original binding energy per nucleon.

Fusion reactions therefore release a greater proportion of the mass–energy available than do fission reactions.

SECTION REVIEW 8.7

REMEMBERING

1 State the speed of light.

2 Recall Einstein's mass–energy equivalence relationship. Define each term in the equation.

UNDERSTANDING

3 Use the graph of binding energy per nucleon to determine the average binding energy of:

a iron

b bromine

c oxygen

d uranium

e helium.

4 Explain what the mass defect is and how it relates to the energy released in a nuclear reaction.

APPLYING

5 Calculate the mass defect and the energy released in the following nuclear fission reaction:

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{90}_{38}\mathrm{Sr} + ^{143}_{54}\mathrm{Xe} + 3\,^{1}_{0}\mathrm{n} + \mathrm{energy}$$

Use the mass values provided below:

unified atomic mass unit, $\mathrm{u} = 1.66 \times 10^{-27}\,\mathrm{kg}$

rest mass of neutron, $m_{\mathrm{n}} = 1.008\,66\,\mathrm{u}$ or $1.674\,38 \times 10^{-27}\,\mathrm{kg}$

rest mass U-235 $= 235.1727\,\mathrm{u}$ or $3.9039 \times 10^{-25}\,\mathrm{kg}$

rest mass Sr-90 $= 87.6200\,\mathrm{u}$ or $1.6423 \times 10^{-25}\,\mathrm{kg}$

rest mass Xe-143 $= 142.9351\,\mathrm{u}$ or $2.3727 \times 10^{-25}\,\mathrm{kg}$

6 Calculate the mass defect and the energy released in the following nuclear fission reaction:

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{144}_{55}\mathrm{Cs} + ^{90}_{37}\mathrm{Rb} + 2\,^{1}_{0}\mathrm{n} + \mathrm{energy}$$

Use the mass values provided below:

unified atomic mass unit, $\mathrm{u} = 1.66 \times 10^{-27}\,\mathrm{kg}$

rest mass U-235 $= 235.1727\,\mathrm{u}$ or $3.9039 \times 10^{-25}\,\mathrm{kg}$

rest mass Cs-144 $= 143.9321\,\mathrm{u}$ or $2.3893 \times 10^{-25}\,\mathrm{kg}$

rest mass Rb-90 $= 89.9148\,\mathrm{u}$ or $1.4926 \times 10^{-25}\,\mathrm{kg}$

7 Calculate the mass defect and the energy released in the following nuclear fusion reaction:

$$^{2}_{1}\mathrm{H} + ^{2}_{1}\mathrm{H} \rightarrow ^{3}_{1}\mathrm{H} + ^{1}_{1}\mathrm{H} + \mathrm{energy}$$

Use the mass values provided below:

unified atomic mass unit, $\mathrm{u} = 1.66 \times 10^{-27}\,\mathrm{kg}$

rest mass H-1 $= 1.007\,83\,\mathrm{u}$ or $1.673\,00 \times 10^{-27}\,\mathrm{kg}$

rest mass H-2 $= 2.013\,55\,\mathrm{u}$ or $3.342\,49 \times 10^{-27}\,\mathrm{kg}$

rest mass H-3 $= 3.016\,05\,\mathrm{u}$ or $5.006\,64 \times 10^{-27}\,\mathrm{kg}$

8 Calculate the mass defect and the energy released in the following nuclear fusion reaction:

$$^{2}_{1}\mathrm{H} + ^{3}_{1}\mathrm{H} \rightarrow ^{4}_{2}\mathrm{He} + ^{1}_{0}\mathrm{n} + \mathrm{energy}$$

Use the mass values provided below:

unified atomic mass unit, $\mathrm{u} = 1.66 \times 10^{-27}\,\mathrm{kg}$

rest mass of neutron, $m_{\mathrm{n}} = 1.008\,66\,\mathrm{u}$ or $1.674\,38 \times 10^{-27}\,\mathrm{kg}$

rest mass H-2 $= 2.013\,55\,\mathrm{u}$ or $3.342\,49 \times 10^{-27}\,\mathrm{kg}$

rest mass H-3 $= 3.016\,05\,\mathrm{u}$ or $5.006\,64 \times 10^{-27}\,\mathrm{kg}$

rest mass He-4 $= 4.026\,43\,\mathrm{u}$ or $6.683\,87 \times 10^{-27}\,\mathrm{kg}$

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CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 Define the following terms.
   a nucleon
   b nuclear fission
   c nuclear fusion
   d nuclear binding energy
   e transmutation.

2 Define 'mass defect' and explain how it relates to the mass–energy equivalence relationship.

3 Specify the relationship between the number of protons and neutrons in an atom and the mass number and atomic number.

CATEGORY QUESTIONS

4 Contrast the electromagnetic force with the gravitational force at the atomic level.

5 Describe the features necessary to sustain a nuclear fission chain reaction.

6 Contrast artificial transmutations with natural transmutations.

ELABORATION QUESTIONS

7 Explain why the binding energy per nucleon is more useful for comparing reactions than simply the binding energy.

8 Describe why the megaelectron-volt (MeV) is a preferred unit for the energy liberated in an individual nuclear reaction.

9 Identify what distinguishes the strong nuclear force from the weak nuclear force.

EVIDENCE QUESTIONS

10 Perform research into the use of nuclear fission for power generation and outline the evidence to support its use for baseload energy.

11 Predict the impact on the global climate if scientists were able to effectively control the nuclear fusion reaction to generate electricity.

12 Explain how the discovery of the enormous energy released with the splitting of the atom affected the outcome of World War II.

END-OF-CHAPTER EXAM

End-of-chapter test

1 In a nuclear fission reaction, the nucleus:

A splits in half.

B splits into two or more fission fragments.

C absorbs energy.

D explodes uncontrollably.

2 In a thermal nuclear fission reactor, 2 kg of mass is converted into energy. Assuming 100% efficiency, determine the amount of energy generated.

A 6.0×10^8 J

B 9.0×10^{16} J

C 1.8×10^{17} J

D 3.6×10^{17} J

3 For the equation for the nuclear fusion reaction below, determine the values of x and y.

$${}^{2}_{1}H + {}^{x}_{1}H \rightarrow {}^{3}_{1}H + {}^{1}_{y}H + \text{energy}$$

A $x = 1, y = 1$

B $x = 1, y = 2$

C $x = 2, y = 2$

D $x = 2, y = 1$

4 Determine the equivalent energy value of 1.50×10^{-28} kg, in joules and megaelectron-volts, MeV.

A 1.35×10^{-11} J, 8.4375×10^7 MeV

B 1.35×10^{-11} J, 84.375 MeV

C 4.50×10^{-20} J, 2.813×10^{-7} MeV

D 2.023×10^{-13} J, 1.265 MeV

5 List, in order of increasing strength, the four forces that act within the nucleus.

6 State Einstein's mass–energy equivalence relationship. Define each term.

7 In a moderate nuclear explosion, 0.4 kg of fissile material is converted into energy. Use Einstein's mass–energy equivalence relationship to calculate the energy released into the atmosphere.

8 State the number of protons and neutrons in the radioisotope uranium-235.

9 Contrast the processes of nuclear fission and nuclear fusion.

10 Use a diagram to illustrate a chain reaction that occurs within a nuclear reactor.

11 Explain why xenon-140 is likely to be involved in fission, and carbon-12 in fusion.

12 Sketch the graph of binding energy per nucleon versus atomic mass number. On the sketch, show the most stable nuclide, where fusion typically occurs and where fission typically occurs.

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13 A slow neutron of mass 1.0086 u causes fission of U-235 (235.044 u). The fission fragments and their masses, in unified atomic mass units, are I-131 (130.906 u) and Y-103 (102.945 u).

a How many neutrons are released in this fission event?

b Calculate the mass defect of this event in unified atomic mass units and in kilograms.

c How much energy is released? Give your answer in joules.

14 In a nuclear reaction that starts with U-233, a slow neutron of mass 1.0086 u causes fission of U-233 (233.044 u). The fission fragments and their masses, in unified mass units, are Mo-104 (103.91 u) and Sn-126 (125.91 u).

a How many neutrons are released in this fission event?

b Write the nuclear fission reaction using correct nuclide and nucleon symbols.

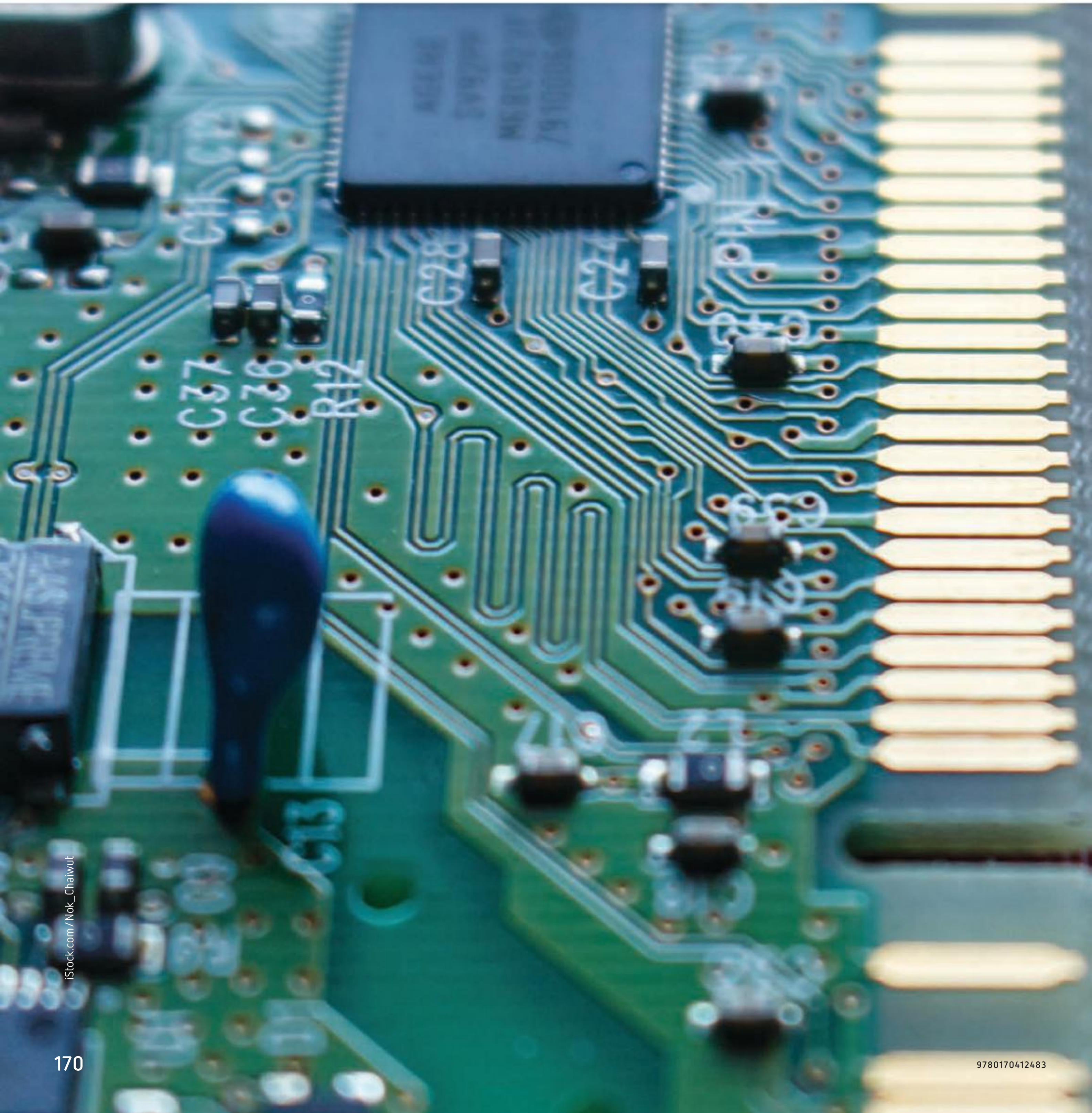
c Calculate the mass defect in this event in unified atomic mass units and in kilograms.

d Determine how much energy is released. Give your answer in joules.

15 Which form of nuclear energy, fission or fusion, has the greatest potential to reduce the negative effects of climate change? Justify your response.

» TOPIC 3

THERMAL, NUCLEAR AND ELECTRICAL PHYSICS



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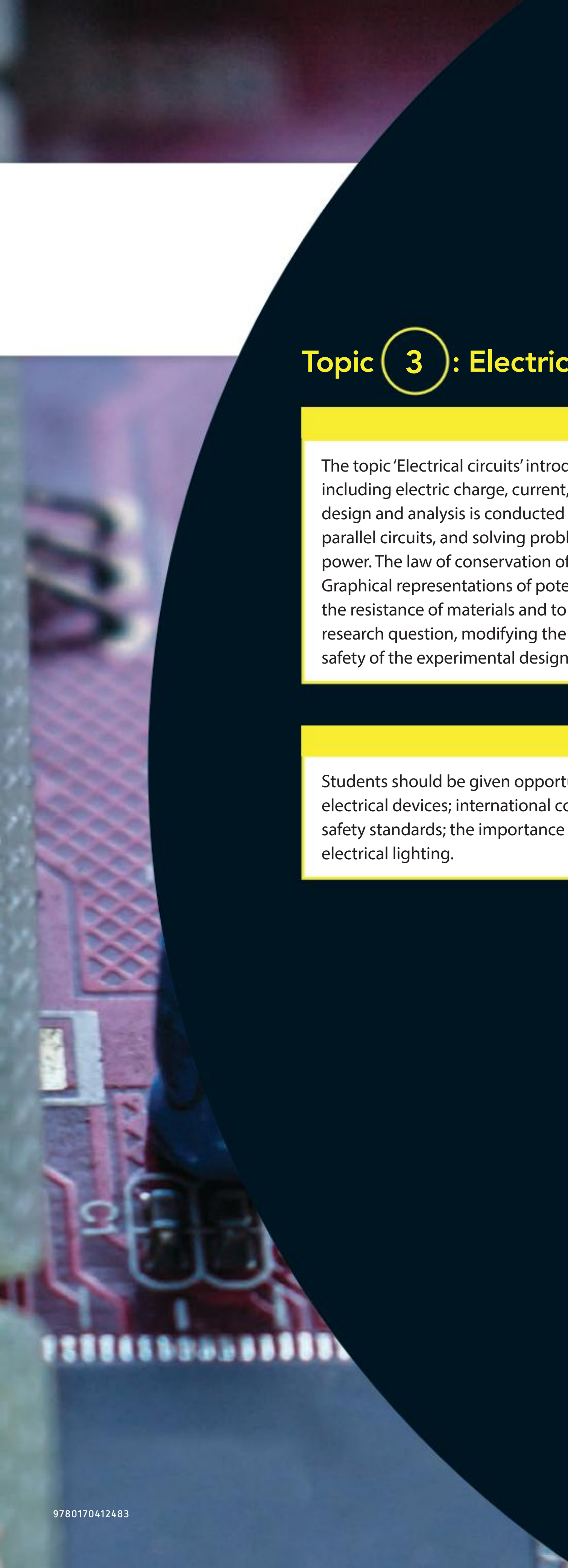


Topic 3: Electrical circuits

The topic 'Electrical circuits' introduces students to the terms associated with electrical circuits including electric charge, current, potential difference, voltage, resistance and power. Simple circuit design and analysis is conducted through presenting circuit components, designing series and parallel circuits, and solving problems to determine current, voltage and resistance values as well as power. The law of conservation of charge and Kirchhoff's current and voltage laws are also applied. Graphical representations of potential difference and current will be interpreted to determine the resistance of materials and to classify them as ohmic or non-ohmic. Practical skills in writing a research question, modifying the methodology, collecting sufficient valid data and considering the safety of the experimental design are addressed.

SCIENCE AS HUMAN ENDEAVOUR

Students should be given opportunities to investigate: the development of and improvement of electrical devices; international cooperation between scientists in the development of electrical safety standards; the importance of reliable electricity in contemporary society; improvements in electrical lighting.

KEY FORMULAS

$$I = \frac{q}{t}$$

$$V = \frac{w}{q}$$

$$P = \frac{W}{t}$$

$$R = \frac{V}{I}$$

$$P = VI$$

$$P = I^2R$$

$$V_t = V_1 + V_2 + \ldots V_n$$

$$R_t = R_1 + R_2 + \ldots R_n$$

$$I_t = I_1 + I_2 + \ldots I_n$$

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots \frac{1}{R_n}$$

9 CURRENT, POTENTIAL DIFFERENCE AND ENERGY FLOW

Introduction

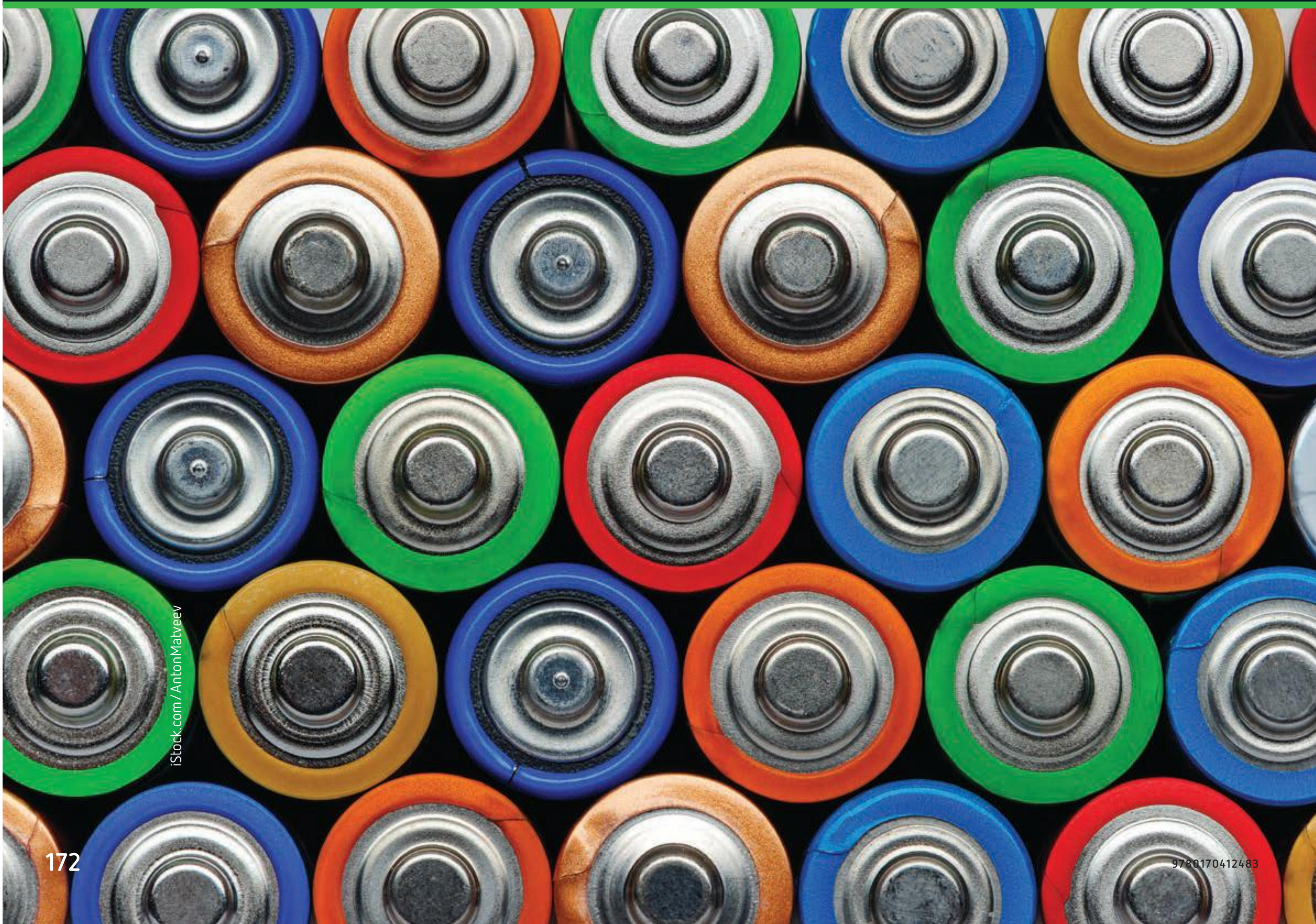
Electricity is a convenient form of energy that is available from both renewable and non-renewable sources. Electricity can be transmitted over great distances and is used domestically, commercially and industrially. Electrical energy can be transformed into other types of energy such as heat, sound, light and mechanical energy.

In this chapter the laws of conservation of charge and of energy are explained and applied to electrical circuits, and steps to solve and analyse circuits are detailed.

Stimulus questions

How is it that you can get an electric shock when opening a car door on a windy day?

Why does turning on an extra appliance at home sometimes cut the power to a circuit?



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9.1 Positive and negative charge carriers

Electricity is a very convenient form of energy. It is available from many sources, such as batteries, alternators and solar panels. It can be generated by power stations that use coal, water (hydroelectricity), natural gas, wind or nuclear fuel. Electrical power is transmitted over large distances for domestic, commercial and industrial use. Electrical energy is easily transformed into other types of energy, such as radiant heat energy in toasters, ovens and heaters; radiant sound energy in speakers in headphones; radiant light energy in incandescent, fluorescent and LED lights; and mechanical kinetic energy in refrigerator motors, electric drills and hair dryers. Energy can also be used in other appliances to operate logic circuits in alarms, computers, robots and controlling devices.

Energy can be transferred from place to place. It can be transformed from one form to another. Energy in an isolated system is conserved. These important concepts will be developed further in this chapter.

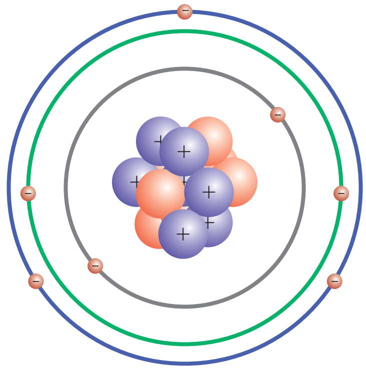

FIGURE 9.1.1 The Rutherford–Bohr model of the atom. Protons and neutrons are located within the nucleus of the atom, while electrons are located in discrete energy level shells outside the nucleus.

Positive and negative charges

The kinetic particle model of matter involves understanding the nuclear model of the atom. For the Rutherford–Bohr model of an atom, a very small central nucleus is surrounded by **electrons**, arranged in differing energy levels. The positively charged nucleus comprises both positively charged **protons** and neutral, uncharged **neutrons** (collectively called nucleons). Almost all of the mass of the atom is found within the nucleus. Electrons, which are negatively charged and make up a very small proportion of the mass, circulate in the region of space around the nucleus in discrete energy level shells (Figure 9.1.1).

electron
a negatively charged subatomic particle and the primary charge carrier in conductors; $q_e = -1.60 \times 10^{-19}$ C

proton
a positively charged subatomic particle found within the atomic nucleus; $q_p = +1.60 \times 10^{-19}$ C

neutron
a neutrally charged subatomic particle within the nucleus of an atom. The mass of a neutron is approximately the same as that of a proton

metallic lattice
a regular arrangement of large numbers of metal atoms that allows free electrons to move readily

TABLE 9.1.1 Relative mass and charge of sub-atomic particles

	PROTON	NEUTRON	ELECTRON
Relative mass	1	1	1/10 000
Charge	+1	Neutral	−1

Metals such as copper and gold are good conductors of heat and of electricity. The arrangement of atoms within a metal is in the form of a **metallic lattice** (Figure 9.1.2). The lattice structure allows electrons that are delocalised to move freely throughout the metal. As a result, metals allow the conduction of electricity.

Charge carriers

Static electricity is the build-up of electric charge on an object. There are many familiar examples of the effects of electrostatic charge: a plastic comb run through hair or a plastic ruler rubbed on woollen material attract small pieces of tissue paper; sometimes a crackling noise can be heard and flashes of light observed when a person takes off a polyester or nylon top in the dark; when a balloon is rubbed near hair and then held a few centimetres away, this causes the hair to stick to the balloon.

All objects are made of atoms and, consequently, all objects are made of positively charged protons, negatively charged electrons and neutrons with no charge. The overall sum of charges on a neutral object is zero – there is the

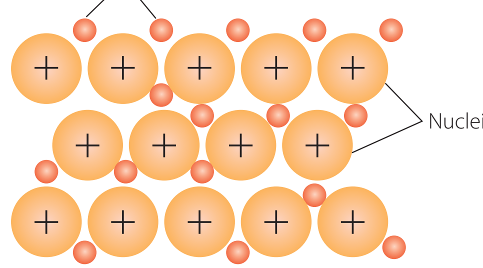

FIGURE 9.1.2 The lattice structure of metals allows delocalised electrons the ability to flow freely throughout the metal; hence, metals conduct electricity.

static electricity charges at rest, or stationary; typically produced on insulators by friction between two surfaces

same number of positive and negative charges. A positively charged object has more positive charges than negative charges. A negatively charged object has more negative charges than positive charges. When an object becomes charged, it is due to the transfer of negatively charged electrons either to the object, making it negatively charged, or away from the object, making it positively charged.

Electric charge can be positive or negative

potential energy energy that is stored in a system due to the configuration and interaction of the bodies within the system

Charge is an intrinsic property of an object. Charge cannot be created or destroyed, but it can move from one object to another. In everyday language, charge is used to mean a form of energy. We say we 'charge' our phone, but this is not scientifically accurate. When you charge your phone, you are providing energy to the battery in order to separate charge. The battery separates the charge using chemical reactions. This separated charge is stored as electrical **potential energy** until it is needed. The charge itself is not energy, but the charged object can be given energy or it can store energy.

If two charged objects of the same net charge (both positively charged or both negatively charged) come near each other, they push away from each other; that is, like charges repel. If two charged objects have the opposite net charge (one positively charged, one negatively charged), they come towards each other; that is, opposite charges attract. Charges are known to exist due to this electrostatic force, which is experienced as attraction or repulsion.

Like charges repel, opposite charges attract

A neutral object has the same number of positive charges as negative charges. Neutral objects do not attract or repel other neutral objects. The amount of charge on an object depends on the difference between the number of protons and the number of electrons.

For example, if two balloons are blown up and held near each other they do not repel or attract each other, they stay still. The balloons are both neutral because they have the same number of protons and electrons. Because they are both neutral, there is no attraction or repulsion (Figure 9.1.3(a)).

If one of the balloons is rubbed on a person's hair, electrons move from the hair onto the balloon. The balloon now has more electrons than protons, which means it has an overall negative charge. The person's hair has lost some of its negative charge, so its overall charge is positive. The positive charge on the hair is attracted to the negative charge on the balloon (Figure 9.1.3(b)).

If both the balloons are rubbed on a person's hair, the balloons are both negatively charged; they have more electrons than protons. As like charges repel, the balloons move away from each other (Figure 9.1.3(c)).

If one of the balloons is recharged on a person's hair and then held near a neutral scrap of paper, the negatively charged balloon attracts the neutral paper. A charged object attracts neutral objects because the charges in the neutral object rearrange themselves. This rearrangement means that the local area nearest the charged object attracts the charged object to the neutral object (Figure 9.1.3(d)).

9.1.1 Balloons and electrical charge

9.1.2 The science of static electricity

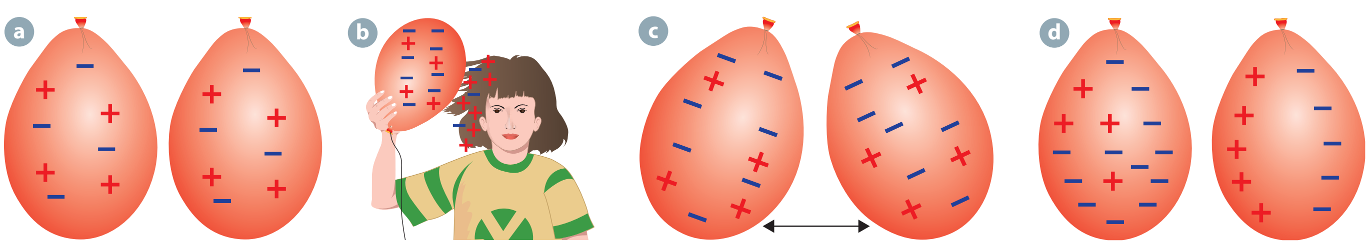

FIGURE 9.1.3 (**a**) Two neutral balloons do not attract or repel. (**b**) Electrons move from your hair onto the balloon. There are more electrons than protons, so the balloon has an overall negative charge. (**c**) Both balloons have an overall negative charge, which causes them to repel. (**d**) The large negative charge on the balloon causes a local rearrangement of charges on a neutral balloon. The neutral balloon is attracted to the negatively charged balloon.

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PRACTICAL ACTIVITY 9.1.1

Investigating electrostatic charge

AIM

To investigate the electrostatic effect of positive and negative charges on a range of objects

MATERIALS

- plastic straws
- paper serviettes
- glass or Perspex rods
- wool or fur (for charging the rods)
- cotton thread
- retort stand
- latex balloon

WHAT ARE THE RISKS IN DOING THIS EXPERIMENT?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
There is a minimal risk of a very small electric shock.	As the magnitudes of the charges are quite small, similar to the size that you might get from discharging a car door, there is no risk management required.

RISK ASSESSMENT

PROCEDURE

1. Rub a straw with a paper serviette to charge the objects and place the serviette against different vertical surfaces. Note how the serviette behaves. (Does it behave differently on a metal surface from a non-metal surface?)
2. Rub a second straw with a serviette to charge it also. Bring the two charged straws near each other. Note how the straws behave.
3. Attach a straw to a length of cotton thread (15 cm). Suspend the straw by the thread from a retort stand. Charge both the straw and the glass or Perspex rod on the wool or fur. Hold the charged rod near the suspended straw. Note how the suspended straw behaves.
4. Blow up the balloon and tie it off. Turn on a tap to a very fine but consistent flow. Charge the balloon by rubbing it against the wool or fur. Bring the balloon close to, but not touching, the flow of water. Note how the water behaves.
5. Take another serviette and rip it into a large number of very small pieces and place them on a desk. Charge the glass or Perspex rod on the wool or fur. Hold the charged rod near the very small pieces of paper. Note how the pieces of paper behave.

DISCUSSION

1. Describe your findings for each experiment. Use the terms 'attract' and 'repel' where possible.
2. Compare your findings to those of others in your class.
3. What conclusions might you draw?

Measuring charge

If an object has the same number of negative electrons as it does positive protons, then it will be neutral. If an object has more negative electrons than positive protons, it will have an overall negative charge. If an object has more positive protons than negative electrons, it will have an overall positive charge.

KEY FORMULA

The quantity of charge is represented by the symbol q. Charge (q) is measured in coulomb, C. One electron has a charge of -1.60×10^{-19} C. How many electrons equal one coulomb of charge?

Let e equal the number of electrons.

$$1\text{ C} = e \times 1.60 \times 10^{-19}$$

$$e = \frac{1}{1.60 \times 10^{-19}}$$

$$e = 6.25 \times 10^{18}$$

To get one coulomb of charge you need 6.25×10^{18} elementary particles (electrons or protons).

9.1.3 Electric vocabulary

If one electron has a charge of -1.60×10^{-19} C, then is it possible for an object to have a charge of 0.8×10^{-19} C? As you can't have a fraction of an electron, it is impossible to have a charge of 0.8×10^{-19} C. Any amount of charge has to be a multiple of 1.60×10^{-19} C. This discrete unit of charge, $q = 1.60 \times 10^{-19}$ C, was discovered by Robert Millikan (1868–1953) in his famous oil drop experiment of 1910.

Charges on conductors and insulators

insulator
a material that inhibits the flow of electrons, e.g. rubber

conductor
a material that allows the flow of electrons, e.g. metals

If electrons are added to an object, the electrons repel each other and, given the right conditions, can spread out. If that object is an insulator, the electrons cannot spread out on that surface and the charge remains 'static', in one place. If the object is a conductor, the electrons can spread out on the surface and produce an even distribution of charge.

If electrons are removed from a conductor, then there are more positive charges in one area (it is termed locally positive). Because the protons are bound within the nucleus of atoms, they cannot move; however, they attract the electrons that can move from nearby atoms. As a result the electrons distribute themselves evenly among the positive charges (Figure 9.1.4).

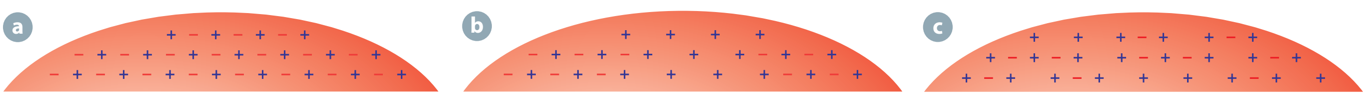

FIGURE 9.1.4 (**a**) A conductor has an even spread of electrons and protons with no net charge. (**b**) Some electrons are removed from the surface of the conductor. There is an excess of protons in one spot. (**c**) The electrons are free to move and are attracted to the positive area. They spread out over the surface to distribute the charge evenly. There is an overall positive charge.

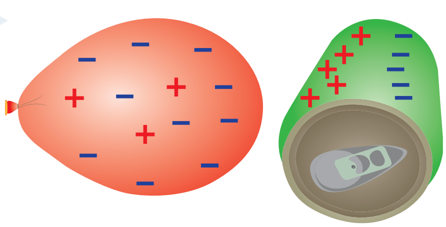

FIGURE 9.1.5 The charges in the soft drink can rearrange themselves because of the negative charge of the balloon.

If an empty soft drink can is laid on its side on a desk and a negatively charged balloon is held near the can, the electrons in the metal are repelled and move to the other side of the can. This means that the side of the can closest to the balloon has a positive charge and is attracted to the balloon (Figure 9.1.5). Although the can is neutral overall, the side closest to the balloon is locally positive, and closer, hence there is a larger electrostatic attraction.

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SECTION REVIEW 9.1

REMEMBERING

1 Define:
   a static electricity
   b potential energy
   c insulator
   d conductor.

2 Which of the following amounts of charge is possible? You may select more than one answer.
   A 1.2×10^{-19} C
   B 2.4×10^{-19} C
   C 4.0×10^{-19} C
   D 4.8×10^{-19} C

UNDERSTANDING

3 State the charges on a proton, a neutron and an electron.

4 Draw a table to compare the relative mass and the position of the elementary particles (proton, neutron, electron).

APPLYING

5 A positively charged conductor is moved towards a neutral conductor.
   a Use a diagram to show what occurs to the charges on the neutral conductor.
   b Explain whether the neutral conductor will be attracted, repelled or neither.
   c Use a diagram to show what happens if the positively charged conductor touches the neutral conductor.

9.2 Conservation of charge

The law of conservation of charge

Like energy, charge is also conserved within an isolated system. The net charge in a system can only be increased by adding charges from outside of the system or decreased by removing charges from the system. This phenomenon is called the **law of conservation of charge**.

This law is applicable to the flow of charge over time, that is, current, as described by Kirchhoff's current law.

law of conservation of charge
the net charge within an isolated system is constant

Kirchhoff's current law

There are basic rules that apply to the analysis of electrical circuits that will assist in determining unknown values. Kirchhoff's first law expresses the conservation of electric charge. It is also referred to as **Kirchhoff's current law**.

Let us look at the current as it travels around the parallel circuit shown in Figure 9.2.1. The current travels from the positive terminal towards the first junction. Some of the current then travels towards point B, while the rest of the current travels towards point C. At the second junction, all of the current comes back to the one path and passes through point D. At each junction the total current entering the junction is equal to that exiting the junction.

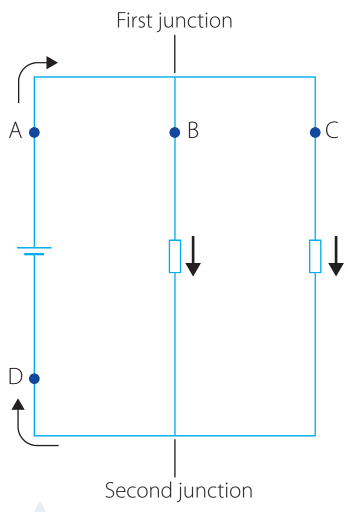


FIGURE 9.2.1 The electric current flowing through a parallel circuit splits at one junction, but then re-joins later. The total current flowing into a junction is the same as the total current leaving the junction.

Kirchhoff's current law (first law)
the total current arriving at a junction within an electrical circuit is equal to the total current leaving the junction

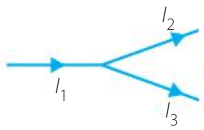


FIGURE 9.2.2 Kirchhoff's current law (first law) The total current arriving at a junction within an electrical circuit is equal to the total current leaving the junction: $I_1 = I_2 + I_3$.

Charge is conserved. The total number of charges entering a junction is the same as the number of charges leaving the junction. This means that the sum of all of the currents going into a junction is the same as the sum of all the currents out of that junction (Figure 9.2.2).

KEY FORMULA

Total current into a junction = total current out of the junction

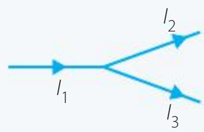
$\Sigma I_{in} = \Sigma I_{out}$ or $I_t = I_1 + I_2 + \ldots I_n$

Where:

I = current (A)

WORKED EXAMPLE 9.2.1

In the diagram, $I_1 = 3\,A$ and $I_2 = 1\,A$. What is the value of I_3?



ANSWER

Using Kirchhoff's current law, total current into a junction = total current out of the junction:

$I_1 = I_2 + I_3$

Rearrange the equation to find the unknown:

$I_3 = I_1 - I_2$

Substitute known values and calculate the answer:

$I_3 = 3\,A - 1\,A$

$I_3 = 2\,A$

SECTION REVIEW 9.2

REMEMBERING

1 Are the following statements true or false?

a The amount of current changes at different points in a series circuit.

b The potential energy changes at different points in a series circuit.

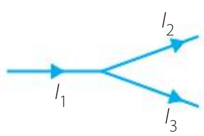
2 State the law of conservation of charge.

UNDERSTANDING

3 Explain Kirchhoff's current law.

APPLYING

4 Use the diagram to answer the following questions.



a If $I_1 = 100\,mA$ and $I_2 = 10\,mA$, what is the value of I_3?

b If $I_2 = 0.75\,A$ and $I_3 = 1.5\,A$, what is the value of I_1?

9.3 Simple electrical circuits and batteries

Electrical circuits involve energy and the movement of charge. When charges move around the circuit they can lose or gain potential energy.

When there is an excess of charge on a conductor, the electrons are repelled from each other and move so that the charge is distributed more evenly. This same concept can be applied to see how a battery provides energy to an **electrical circuit**. An electrical circuit is a complete loop through which charge can flow. If the loop is not complete, then charge cannot flow.

electrical circuit a complete conducting loop through which charge can flow

electromotive force, EMF source of potential energy per charge (voltage)

Figure 9.3.1 shows a light globe, switch and a battery connected by conducting wires. This is an example of a simple electrical circuit.

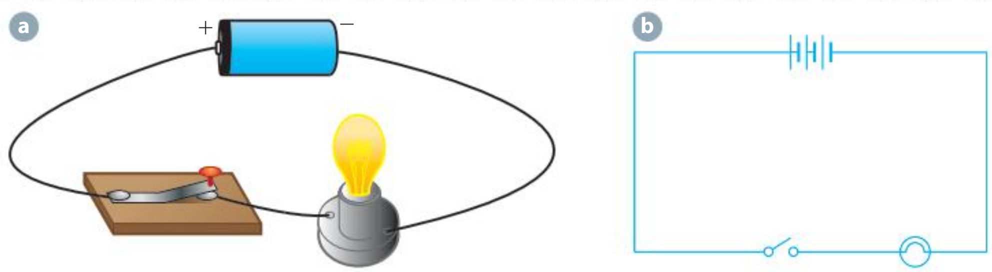


FIGURE 9.3.1 (**a**) A simple electrical circuit comprising a potential rise (battery), switch and a potential drop (light globe) (**b**) A circuit diagram of an equivalent circuit.

Batteries

A battery is a source of potential energy per charge, or **electromotive force** (EMF). In a charged battery, a chemical reaction separates the positive and negative charges. There are many like charges close together in separate parts of the battery, giving the charges a large amount of potential energy. In a circuit, the negative terminal of the battery is connected to the positive terminal by connecting wires. The build-up of electrons in the negative terminal causes the electrons in the wire to move towards the positive terminal.

Figure 9.3.3 shows a simple circuit with a battery and a light globe. Electrons near the negative terminal (e.g. electron *a*) have a high potential energy – they are near other electrons. As the electrons

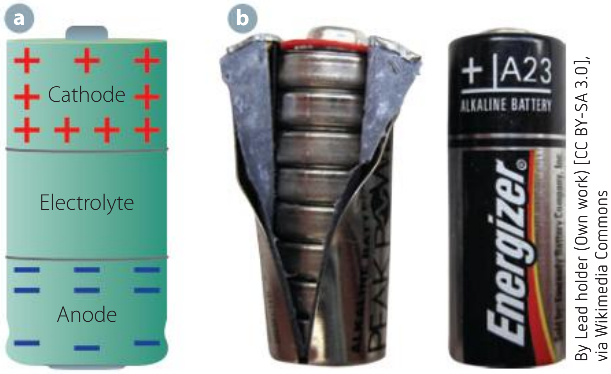


FIGURE 9.3.2 (**a**) A simplified battery. (**b**) An AA battery is a collection of smaller cells.

9.3.1 Circuit construction (AC + DC)

9.3.2 Circuit construction (DC only)

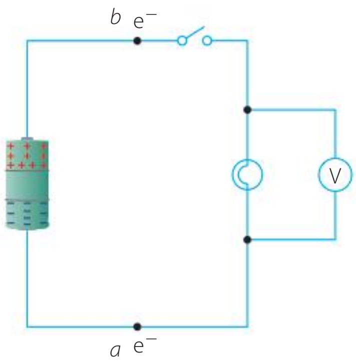


FIGURE 9.3.3 Electron *a* near the negative terminal has a high potential energy. Electron *b* near the positive terminal has a low potential energy. The voltmeter measures the potential energy difference between electron *b* and electron *a*.

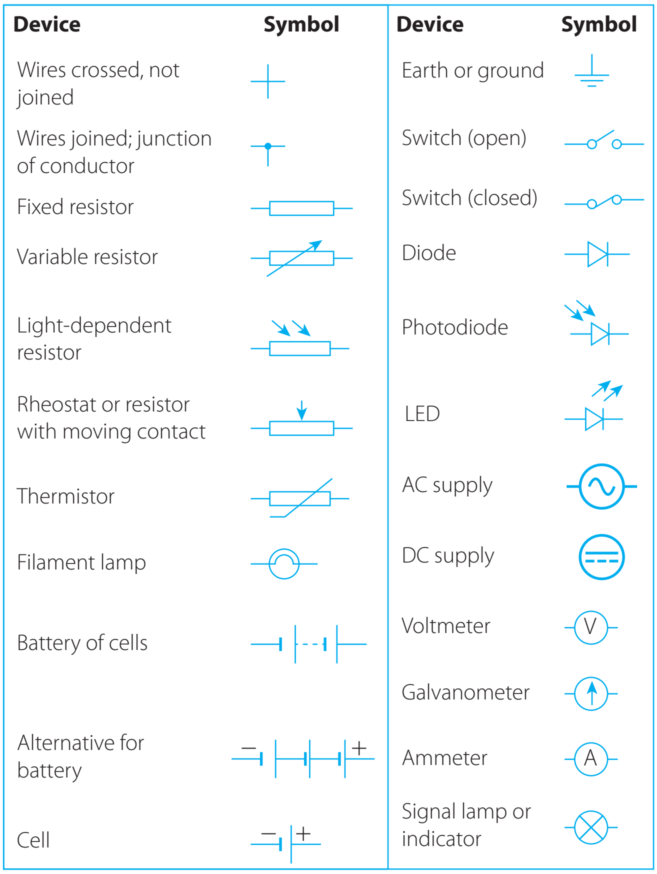


FIGURE 9.3.4 Conventional symbols used in electrical circuit diagrams

move through the circuit, their potential energy is transformed into radiant light and heat in the light globe. Electrons near the positive terminal (e.g. electron *b*) have a low potential energy – they are near many protons. The same logic can be applied to protons when considering conventional current. Protons near the positive terminal have a high potential energy – they are near other protons. Protons near the negative terminal have a low potential energy because they are near electrons. The light globe is an example of a load or potential drop and transforms the energy provided by the source into other forms.

Physicists use symbols to represent different components in circuit diagrams. Some examples of common symbols are shown in Figure 9.3.4. The most important symbols to focus on for now are the battery, light globe (filament lamp), switch and resistor.

Using the symbols to draw the circuit in Figure 9.3.3 (page 179), it would look like Figure 9.3.5.

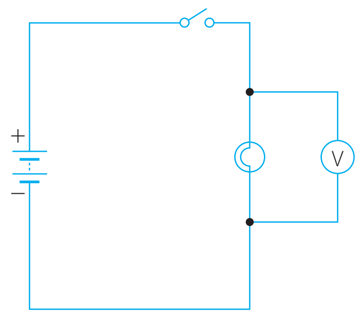


FIGURE 9.3.5 A simple circuit (from Figure 9.3.3) drawn with circuit symbols

SECTION REVIEW 9.3

REMEMBERING

1 Define 'electromotive force'.

2 Draw the circuit symbol for:

- **a** a variable resistor
- **b** a filament lamp
- **c** an AC supply
- **d** an ammeter
- **e** a signal lamp or indicator.

UNDERSTANDING

3 Describe what is required to make an electrical circuit.

4 Explain how the movement of charge allows a battery to store energy.

REFLECTING

5 People often 'charge' their phones when their battery is running low. Are they adding more charge to the phone or is another process taking place? Describe what is happening.

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9.4 Electric current, potential difference and power

Current

When there is an electrical potential difference between two points in a circuit, the negatively charged electrons are attracted towards the positive terminal. This causes the electrons to move along the wire, creating a flow of **current**. This electric current is carried by the discrete charge carrier, the electron, with a charge of $q = 1.60 \times 10^{-19}$ C each. The amount of current, I, depends on the amount of charge, q, that passes a point in a given time, t. The unit of current is the ampere, A. One ampere is equal to one coulomb of charge (or 6.25×10^{18} electrons) passing a given point in one second.

current, I
the rate of flow of charge, that is, charge per unit time; measured in amperes, A:
$I = \frac{q}{t}$

KEY FORMULA

Current, I, is the rate of flow of charge; that is, charge per unit time.

$$I = \frac{q}{t}$$

Where:

I is measured in amperes, A; q is measured in coulombs, C; and t is measured in seconds, s.

KEY FORMULA

1 ampere = 1 coulomb per second

$1\,\text{A} = 1\,\text{C}\,\text{s}^{-1}$

WORKED EXAMPLE 9.4.1

An electron discharge tube produces a beam of electrons with a measured current of 30 mA.

a Determine the amount of charge emitted in 1 minute.

b Calculate the number of charges emitted in 1 minute.

ANSWERS

a State the equation:

$$I = \frac{q}{t}$$

Substitute known values:

$$30 \times 10^{-3}\ \text{A} = \frac{q}{60\ \text{s}}$$

Rearrange the equation to find the unknown:

$q = 30 \times 10^{-3} \times 60\,\text{C}$

Calculate the answer:

$q = 1.8\,\text{C}$

1.8 coulomb of charge is emitted.

b 1.0 C of charge represents 6.25×10^{18} electrons:

$1.8\ \text{C} \times 6.25 \times 10^{18}$ electrons per coulomb $= 1.125 \times 10^{19}$ electrons

1.13×10^{19} electrons are emitted.

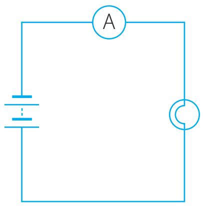


FIGURE 9.4.1 An ammeter is placed in series in the circuit. The amount of charge that passes a point in a given time is $q = It$.

conventional current the convention to describe electrical current as the flow of positive charge

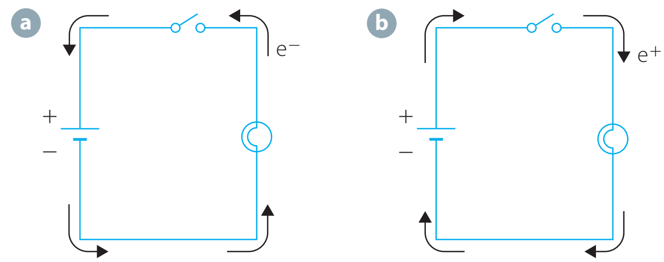
Measuring current

Current is measured with an ammeter. An ammeter measures the amount of charge passing through a point each second. It is inserted within a circuit in series, as shown in Figure 9.4.1.

Conventional current

Up until this point we have talked about current as the flow of electrons because it is the movement of electrons that creates the current in a conducting wire. When scientists were making discoveries about electricity, they were not aware of today's model of the atom nor the mechanism for the movement of charge. As a result they established the convention that electricity be considered flowing in the direction of a positive charge, from positive terminal to negative terminal. This is known as **conventional current**. Physicists have kept the convention because it makes no difference to the laws and rules applied to electromagnetism.

FIGURE 9.4.2 (**a**) Electrons flow from the negative terminal to the positive terminal. (**b**) Conventional current is the flow of positive charge from the positive terminal to the negative terminal.



SCIENCE AS A HUMAN ENDEAVOUR

The development of complex models and/or theories often requires a wide range of evidence from many individuals and across disciplines.

International scientific conventions, such as the use of SI units and 'conventional current' have been adopted as routine practice by scientists, and their consistent use ensures clear communication of ideas and findings across the globe.

Effective communication has enabled scientists to share, collaborate and interrogate each other's' work as never before. Complex global scientific endeavours such as the Large Hadron Collider (LHC), the Square Kilometre Array (SKA), the International Thermonuclear Experimental Reactor (ITER) and the International Space Station (ISS) have benefitted from the input of scientists of many different nationalities and disciplines.

Perform research into one of these global projects to identify:

a the nature of the project.

b the nationalities of the scientists involved.

c the scientific disciplines represented.

direct current (DC) current that is always in one direction

alternating current (AC) current that changes direction periodically, typically 50 oscillations per second (50 hertz)

root mean square voltage (V_{rms}) AC voltages may be compared to DC voltages by converting the peak voltage to the root mean square voltage, or V_{rms}: V_{peak}

Direct current and alternating current

Electrical energy is supplied by either **direct current (DC)** or **alternating current (AC)** sources. In DC, the net charge flows in one direction, and in AC the direction of charge flow alternates periodically.

DC is used in electrical devices such as mobile phones, torches and toys. The most common source of DC is a battery, although many appliances that you use convert AC from your wall sockets into DC, via an adapter (rectifier). AC is used in car alternators, motors and air conditioners. The electrical energy supplied by a power point in the wall is AC because it is simpler to produce and transmit, and power losses in the wires during transmission are minimised. The standard AC power supply in Australia has a potential difference of $240\,V_{rms}$ (**root mean square voltage**) and a frequency of 50 Hz. Different countries have different standards for electricity supply voltage and frequency.

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Potential difference

Electrical potential describes how much potential energy there is per unit of charge at different locations in a circuit. Potential difference is also commonly known as 'voltage'.

Hence, electrical potential difference is measured in units of joules per coulomb, $J\,C^{-1}$, but is commonly termed the volt, V.

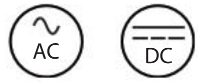

FIGURE 9.4.3 The circuit symbols for alternating current (AC) and direct current (DC) are often seen on power adapters and electrical devices.

Charge separation

Energy is required to separate opposite charges. If a positive and a negative charge are close together they are attracted strongly. If energy is provided then the charges can be pulled apart, providing the charges with energy – electrical potential energy – that is ready to be released. Potential energy is energy that is ready to be transferred or transformed, and hence it provides the potential difference required to make a current flow. If 'let go', the positive and negative charges move towards each other, making an electric current. As the electrons move towards each other they lose potential energy, and it takes work to separate them again. In a similar manner, two like charges (e.g. two electrons) will repel each other more when they are close together than when they are further apart.

The electrical potential is measured relative to some reference point, often the ground or the positive terminal of a battery. Hence what we generally measure is not potential but **potential difference**, which uses the same value and symbol, *V*. The potential difference between two points is simply the difference in potential energy per unit charge between those two points. It is sometimes referred to as 'voltage' because it is measured in volts, V.

KEY FORMULA

The potential energy per unit of charge

$$V = \frac{W}{q}$$

Where:

V = voltage, measured in volts (V)

W = potential energy (or ability to do work), measured in joules (J)

q = charge, measured in coulomb (C)

$1.0\,V = 1.0\,J\,C^{-1}$

potential difference, V a measure of the potential energy per unit of charge. Potential difference and voltage are measured in volts (V); also termed voltage: $V = \frac{W}{q}$

When a charge q moves between two points, it will lose or gain electrical potential energy. The energy change – loss or gain – is equal to the work done to move the charge, and is written as $W = qV$. Again, V is the voltage, measured in volts, V, W is the work (or energy), measured in joules, J, and q is the charge, measured in coulombs, C.

The potential difference between two points in a circuit is measured with a voltmeter. The voltmeter needs to be connected in parallel to two different parts of the circuit, as shown in Figure 9.4.4

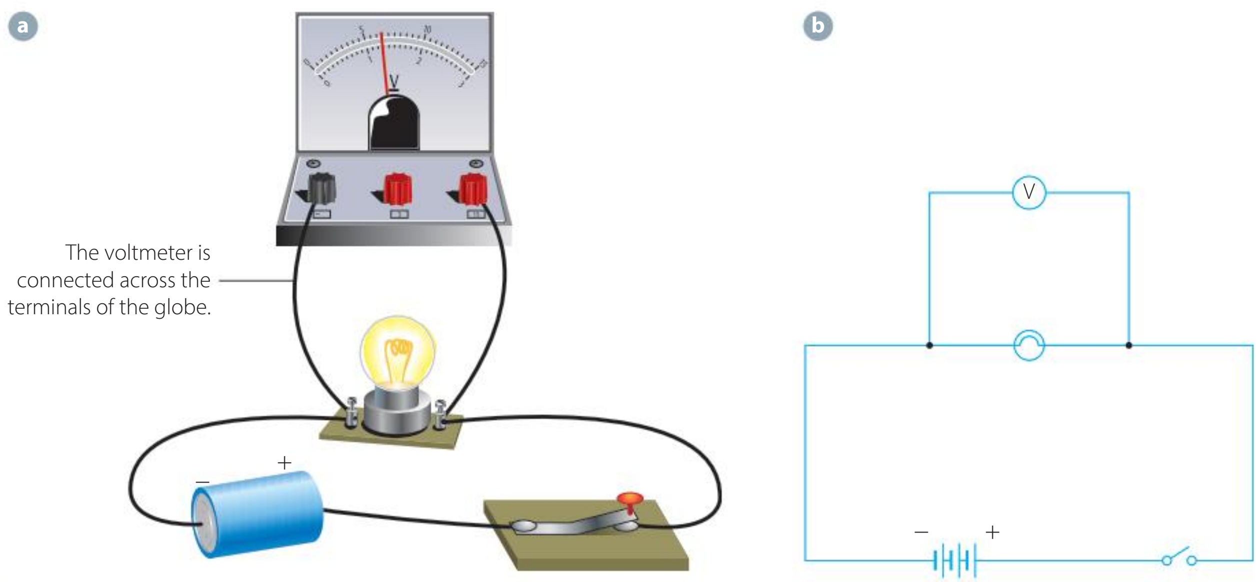

FIGURE 9.4.4 (**a**) The voltmeter measures the potential difference between any two points. It is placed in parallel across an element within the circuit. (**b**) The circuit can be represented as a circuit diagram.

WORKED EXAMPLE 9.4.2

Determine the voltage applied across a resistor if 90 joules of work is done by 10 C of charge.

ANSWER

State the equation:

$$V = \frac{W}{q}$$

Substitute known values:

$$V = \frac{90\ \text{J}}{10\ \text{C}}$$

Calculate the answer:

$V = 9$ V

power, P
a measure of the rate of energy transformation per unit of time

Power

For a light globe to glow it needs to be provided with an energy source, such as a battery. The light globe transforms the electrical energy into radiant light and heat energy. It is useful to know how quickly this energy is being transformed. **Power** is a measure of the rate of energy transformation per unit of time. Power is measured in watts (W), which is equivalent to a joule per second, as well as a volt-ampere.

$$1.0 \text{ watt} = 1.0 \text{ joule per second} = 1.0\,\text{J s}^{-1} = 1.0 \text{ volt-ampere}$$

For example, a 100 W globe converts 100 J of energy in 1 second. A 50 W globe takes 2 seconds to convert the same amount of energy. The 100 W globe is therefore more powerful because it uses more energy per second than the 50 W globe. It is twice as powerful because it converts energy at twice the rate.

KEY FORMULA

$$P = \frac{W}{t} = V \times I$$

Where:

V is measured in volts (V)

I is measured in amperes (A)

t is measured in seconds (s)

energy (or work, W) is measured in joules (J)

Power is then measured in watts (W):
1 watt = 1 W = 1 joule per second = $1\,\text{J s}^{-1}$

WORKED EXAMPLE 9.4.3

An electric toaster is measured to use 108 kJ of energy while operating for 1 minute. What is the power rating of the toaster?

ANSWER

State the equation:

$$P = \frac{W}{t}$$

Substitute known values and calculate the answer:

$$P = \frac{108\,000\ \text{J}}{60\ \text{s}}$$

$P = 1800$ W

Energy and power

Power delivery within an electrical circuit can also be deduced from voltage and current values:

$$P = \frac{W}{t}$$

$$P = \frac{Vq}{t} = V\frac{q}{t}$$

$$P = VI$$

and the amount of energy transferred can be deduced from using $P = V \times I$:

$$P = \frac{W}{t}$$

$$W = Pt$$

$$W = VIt$$

WORKED EXAMPLE 9.4.4

An air conditioner operates at 240 V and draws a current of 10 A.

a Calculate its power rating.

b Determine how much energy was used (work was done) by the air conditioner in 4 hours.

ANSWERS

a State the equation for power:

$P = V \times I$

Substitute known values and calculate the answer:

$P = 240\,\text{V} \times 10\,\text{A}$

$P = 2400\,\text{W}$

b State the equation for work:

$W = V \times I \times t$

Substitute known values and calculate the answer:

$W = 240\,\text{V} \times 10\,\text{A} \times (4 \times 60 \times 60)\,\text{s}$

$W = 34\,560\,000\,\text{J}$

Give the answer in the appropriate unit:

$W = 34.56\,\text{MJ}$

Energy units

The SI unit for energy, the joule, is often too small to be convenient when measuring the energy use of household appliances. Electricity companies use the larger unit of the **kilowatt hour (kWh)** for the purpose of charging for electricity consumption.

To derive the conversion of energy values from kilowatt-hours to joules, follow the process below. One kilowatt-hour (1 kWh) is the *energy* used by a 1 kW appliance in 1 hour:

$E\,(\text{kWh}) = P\,(\text{kW}) \times t\,(\text{h}) = 10^3\,\text{W} \times (60\,\text{min}\,\text{h}^{-1} \times 60\,\text{s}\,\text{min}^{-1})$

Thus: 1.0 kilowatt-hour $= 1.0\,\text{kWh} = 3.6 \times 10^6\,\text{J}$

kilowatt hour (kWh)
a convenient measure of electrical energy equal to the power consumption of 1 kilowatt in 1 hour: $1.0\,\text{kWh} = 3.6 \times 10^6\,\text{J}$

WORKED EXAMPLE 9.4.5

A refrigerator is left running continuously for one week while the family is away on holiday. It operates at 240 V and draws a current of 4.0 A.

a Determine the power rating of the refrigerator.

b Calculate the amount of energy used, in MJ, over the week.

c Calculate the amount of energy used, in kWh.

ANSWERS

a $P = V \times I$
$P = 240\,\text{V} \times 4.0\,\text{A}$
$P = 960\,\text{W}$

b $W = V \times I \times t$
$W = 240\,\text{V} \times 4.0\,\text{A} \times (1 \times 7 \times 24 \times 60 \times 60)\,\text{s}$
$W = 580\,608\,000\,\text{J}$
$W = 5.81 \times 10^2\,\text{MJ}$

c $W = 580\,608\,000\,\text{J}$

$$W = \frac{580\,608\,000\ \text{J}}{3.6 \times 10^6\ \text{J per kWh}}$$

$W = 161.3\,\text{kWh}$

SECTION REVIEW 9.4

REMEMBERING

1 Define:

- **a** conventional current
- **b** alternating current
- **c** potential difference
- **d** power.

2 State the conversion between joules and kilowatt hours.

UNDERSTANDING

3 Explain why the kilowatt-hour is used for measuring household energy consumption, rather than the joule.

APPLYING

4 An X-ray machine produces a very high potential difference to accelerate electrons and produce a current of 15 A for 0.5 seconds. Determine the amount of charge produced over this period.

5 A voltage drop of 12 V was measured across a light globe as 15 C of charge passed through it. Determine how much energy was transformed from electrical to radiant light and heat within the light globe.

6 A washing machine requires 540 kJ of energy to complete a single 40-minute load. It is connected to a typical 240 V household circuit.

- **a** Calculate the current drawn by the washing machine.
- **b** Determine the power rating of the machine.

7 Household lighting equivalent to 660 W is left on for 8 hours a day in a typical household (240 V) circuit.

- **b** Determine the amount of energy used, in MJ, on a typical day.
- **c** Determine the amount of energy used, in kWh, in one week.

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9.5 Solving problems: current, charge and time, electrical potential and power

Solving problems is an art that is best learnt by continued practice and by applying some strategy. To solve problems involving current, charge and time, electrical potential and power, complete the following steps:

1. Read the question carefully and try to understand the scenario.
2. Organise the information, particularly the values and units provided.
3. Sketch a diagram of the scenario.
4. Consider what formula may be applied.
5. Verify the units and perform any conversions required.

Problems involving current, charge and time

WORKED EXAMPLE 9.5.1

A current of 2.0 A flows in a 20 cm section of a conducting wire. How many electrons pass through the end of the section every second?

ANSWERS

$$I = \frac{q}{t}$$

$q = I \times t$

$q = 2.0\,\text{A} \times 1\,\text{s}$

$q = 2.0\,\text{C}$

The number of electrons (elementary particles) is thus $q \times 6.25 \times 10^{18}$ electrons C^{-1}.

$e = 2\,\text{C} \times 6.25 \times 10^{18}$ electrons C^{-1}

$e = 1.25 \times 10^{19}$ electrons

1.25×10^{19} electrons pass through the end of the section every second.

Problems involving electrical potential

WORKED EXAMPLE 9.5.2

A resistor has a potential difference across it of 24 volts. Determine the amount of charge required to flow through the resistor to complete 180 joules of work.

ANSWER

$$V = \frac{W}{q}$$

$$q = \frac{W}{V}$$

$$q = \frac{180\,\text{J}}{24\,\text{V}}$$

$q = 7.5\,\text{C}$

Problems involving power

WORKED EXAMPLE 9.5.3

A current of 2.0 A flowing in a heater for 1 hour converts 1.7 MJ of electrical energy into heat energy.

a How much charge was transferred through the heater?

b What potential difference exists across the heater?

c Determine the power rating of the heater, in kW.

d How much energy, in kWh, is used if the heater runs for 2 hours?

ANSWERS

a State the equation:

$$I = \frac{q}{t}$$

Rearrange equation to find the unknown:

$q = It$

Substitute known values:

$q = 2.0\,\text{A} \times (60\,\text{min}\,\text{h}^{-1} \times 60\,\text{s}\,\text{min}^{-1})$

Calculate the answer:

$q = 7.2 \times 10^3\,\text{C}$

b State the equation:

$$V = \frac{W}{q}$$

Substitute known values:

$$V = \frac{1.7 \times 10^6\ \text{J}}{7.2 \times 10^3\ \text{C}}$$

Calculate the answer:

$V = 236.11\,\text{V}$ or $240\,\text{V}$ (rounded to two significant figures)

c $P = VI$
$P = 240\,\text{V} \times 2.0\,\text{A}$
$P = 480\,\text{W}$
$P = 0.48\,\text{kW}$

d $W = P \times t$
$W = 0.48\,\text{kW} \times 2.0\,\text{h}$
$W = 0.96\,\text{kWh}$

SECTION REVIEW 9.5

REMEMBERING

1 Outline the steps to solving problems involving current, charge and time, electrical potential and power.

2 State the charge on an electron.

UNDERSTANDING

3 Determine the number of elementary particles in 1.0 C of charge.

4 Explain how a potential difference creates a flow of electrons.

APPLYING

5 How much charge passes through a load if a current of 4.0 A flows for 5.0 s?

6 A current of 80 mA flows through a circuit. There are 3.0×10^{21} conduction electrons within a 5 cm section. How many electrons pass through the end of this section every second?

7 Given that 3 C of charge flows past a point in a circuit in 30 s, calculate the current flowing.

ANALYSING

8 A heater operates at 240 V and draws a current of 8 A from a household circuit.

- **a** Calculate its power rating.
- **b** Determine how much energy is used (work is done) by the heater if it is used for 6 hours.

9 A resistor has a potential difference across it of 12 V. Given that 450 J of energy is converted to heat as the charge travels through the resistor, determine the amount of charge that flows through the resistor and the number of electrons that this represents.

10 A voltage drop of 9 V was measured across a light globe as 3.0 C of charge passed through it. Determine how much energy was transformed from electrical to radiant light and heat within the light globe.

9.6 Energy input and output in circuits

In any circuit, sources such as batteries and power packs provide potential energy to electrons, and loads, such as resistors and light globes, convert that energy into other forms. In accordance with the law of conservation of charge, the total energy expended throughout a circuit equals the energy provided; that is, the energy input will equal the energy output. Although this is the case for energy, the same cannot be said for current or voltage, as they differ depending on the complexity of the circuit. There are, however, systematic ways to analyse electrical circuits, including the use of Kirchhoff's current law, as previously introduced, and **Kirchhoff's voltage law**.

Kirchhoff's voltage law (second law) for any closed loop in an electrical circuit, the sum of the potential differences must be zero

Kirchhoff's voltage law

In a series circuit, the application of Kirchhoff's voltage law is relatively straightforward, as the potential difference provided by the energy source is shared between the loads.

For example, consider Figure 9.6.1 and suppose that the potential difference across the battery is 12 V. Remember that potential difference is potential energy per unit charge. Let's define the zero of potential energy as being at the negative terminal of the battery. A charge q close to the positive terminal of the battery has potential energy $W = 12\text{V} \times q$. Think about moving around the circuit now. If you do a complete lap from the positive terminal of the battery back to the same point, you return to a point with the same potential energy again. Hence, whatever potential energy was gained by passing through the battery is lost as you pass through the globe and the resistor. We call components such as light globes and resistors loads or potential drops, because potential energy is transformed into other forms ('lost') as a charge passes through these components. The total change in potential around a complete loop in a circuit is zero. That means the total of all positive potential differences equals the total of all negative potential differences.

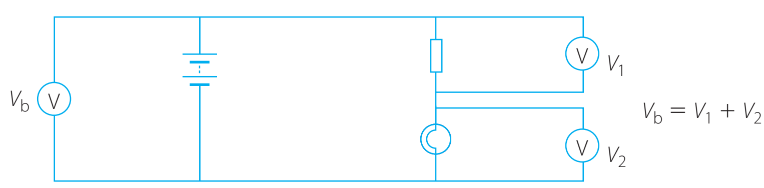

FIGURE 9.6.1 According to Kirchhoff's voltage law, the sum of the potential rise is equivalent to the sum of the potential drops. In a series circuit, the voltage rise from the source is shared, not necessarily equally, between the loads in the circuit.

In Figure 9.6.1 it can be seen that $V_b = V_1 + V_2$. The potential difference provided by the battery is shared between the two loads; that is, the potential rise equals the sum of the potential drops in a series circuit. For example, if the battery provided 12 V and the resistor had a measured voltage of $V_1 = 8$ V, then $V_2 = V_b - V_1 = 12\text{ V} - 8\text{ V} = 4$ V.

Now consider Figure 9.6.2. We have the same components, but now each is connected directly across the battery terminals. We call this a parallel circuit. Applying the same idea as above, if a charge moves around one loop of this circuit, returning to its original position, the potential energy of the charge must be the same as when it started. It doesn't matter which loop we follow, this will always be the case. Hence, the magnitude of the potential difference measured on each voltmeter is the same: $V_b = V_1 = V_2$.

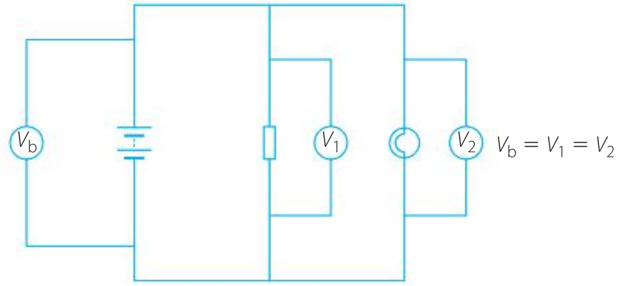

FIGURE 9.6.2 According to Kirchhoff's voltage law, the sum of the potential rise is equivalent to the sum of the potential drops in each individual loop. In a parallel circuit the potential difference provided by the source is shared by the load within a single closed loop.

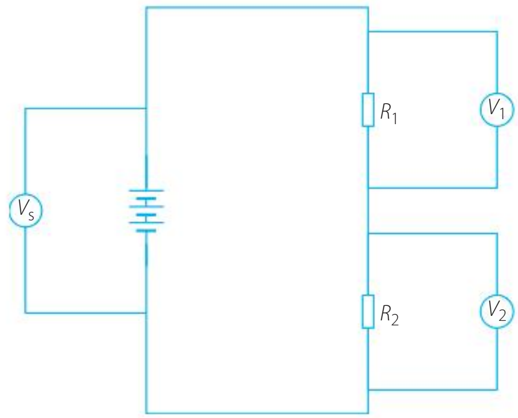

FIGURE 9.6.3 According to Kirchhoff's voltage law, the sum of the potential rise is equivalent to the sum of the potential drops in each individual loop. In a series circuit, the voltage rise from the source is shared, not necessarily equally, between the loads in the circuit.

WORKED EXAMPLE 9.6.1

In Figure 9.6.3, $V_S = 12$ V and $V_1 = 4$ V. Calculate the value of V_2.

ANSWER

According to Kirchhoff's voltage law, the sum of the potential rise equals the sum of the potential difference:

$V_S = V_1 + V_2$

Substitute known values ad calculate the answer:

$12\text{ V} = 4\text{ V} + V_2$

$V_2 = 12\text{ V} - 4\text{ V}$

$V_2 = 8$ V

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WORKED EXAMPLE 9.6.2

In Figure 9.6.4, $V_S = 24\,V$ and $V_2 = 6\,V$. Calculate the value of V_1 and V_3.

ANSWER

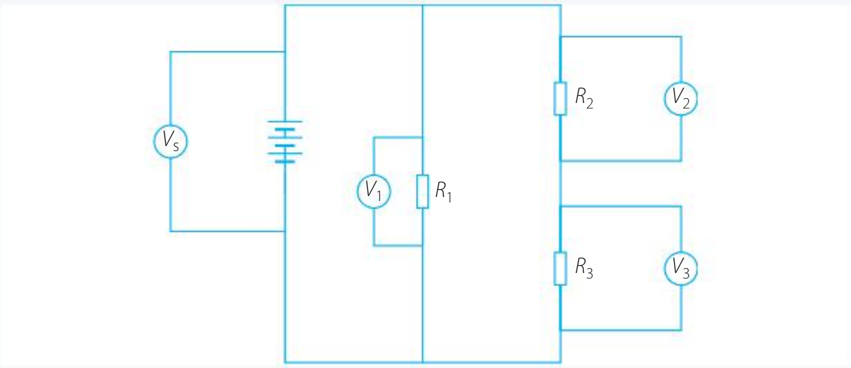


FIGURE 9.6.4

According to Kirchhoff's voltage law, the sum of the potential rise equals the sum of the potential difference in each closed loop. In this case, the voltage supply and R_1 are in one closed loop, while the voltage supply, R_2 and R_3 are in a second closed loop.

For the first closed loop:

$V_S = V_1$

$24\,V = V_1$

$V_1 = 24\,V$

For the second closed loop:

$V_S = V_2 + V_3$

$24\,V = 6\,V + V_3$

$V_3 = 24\,V - 6\,V$

$V_3 = 18\,V$

SCIENCE AS A HUMAN ENDEAVOUR

The increased use of electrical devices, including heating and cooling systems, along with larger homes and population growth worldwide, places greater demand on energy supply, particularly during extreme weather.

The electricity network is complex and must be continually managed to provide sufficient energy to all customers. At times it is necessary for energy providers to create a 'brownout' to save the whole network from power failure.

Conduct research and contrast the terms 'brownout' and 'blackout'. Investigate examples of power failures that have occurred due to heatwaves in Australia, or cold snaps in European winters.

SECTION REVIEW 9.6

REMEMBERING

1 State Kirchhoff's voltage law.

2 State the law of conservation of electric charge.

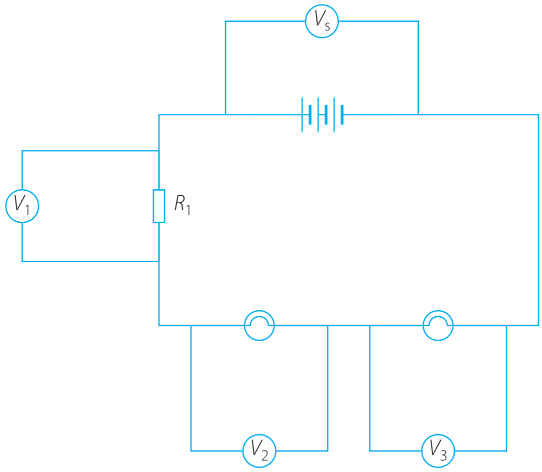
UNDERSTANDING

3 Draw a combination circuit with some elements in series and others in parallel. Label the series components and the parallel components.

APPLYING

4 In Figure 9.6.5, let $V_S = 14\text{ V}$ and $V_1 = 8\text{ V}$. The light globes are identical. Determine the voltage drops V_2 and V_3.

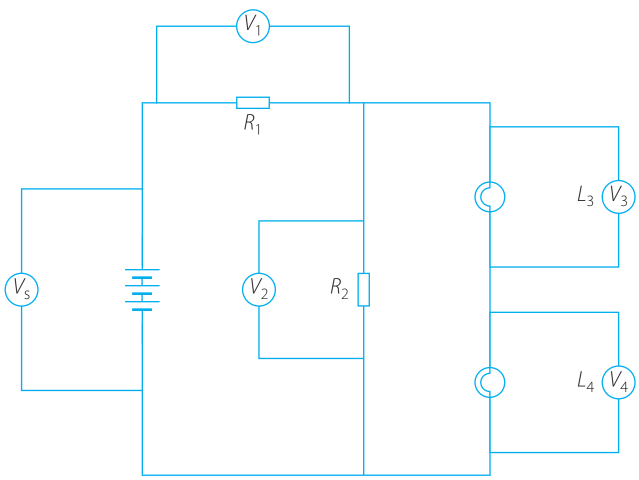
FIGURE 9.6.5



5 In Figure 9.6.5, let $V_1 = 2\text{ V}$ and $V_2 = V_3 = 6\text{ V}$. Determine the supply voltage, V_S.

6 In Figure 9.6.6, let $V_S = 18\text{ V}$ and $V_1 = 4\text{ V}$. The light globes are identical. Determine the voltage drops across V_2, V_3 and V_4.

FIGURE 9.6.6



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CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 Define the following terms.
   a Proton
   b Neutron
   c Electron
   d Metal lattice
   e Current
   f Voltage

2 Explain the factors that can affect the brightness of a light globe in a circuit.

3 Draw the symbols for AC and DC that are typically seen on power adapters and electrical devices.

CATEGORY QUESTIONS

4 Contrast static electricity with current electricity.

5 Describe the device and type of connection necessary to measure the current through a load in a circuit.

6 Explain what distinguishes a conductor from an insulator.

ELABORATION QUESTIONS

7 How does the Rutherford–Bohr model of the atom support the definition of electric current being the flow of charge?

8 Explain the relationship between electric current and conventional current.

9 Refer to the definition of potential difference to justify why light globes in parallel circuits may glow with the same brightness.

EVIDENCE QUESTIONS

10 Perform an audit of your energy use, listing all the electrical devices used each day and for what periods. Identify one area of power use that you could reduce to achieve a smaller carbon footprint.

11 Suppose that scientists were able to make a battery that held 10 times as much charge as an existing battery; predict how this might change the electric car industry.

12 Perform research into Millikan's famous oil drop experiment to explain how he determined that the charge on an individual electron was $q = 1.60 \times 10^{-19}$ C.

END-OF-CHAPTER EXAM

End-of-chapter test

1 The amount of electric charge on an object is determined with reference to:

A the number of electrons on the object.

B the number of protons on the object.

C the number of neutrons on the object.

D the number of protons and electrons on the object.

2 Electrons are removed from an area of a neutral conductor. Which of the following is most likely to happen?

A Protons within the conductor will move towards the area.

B Electrons within the conductor move towards the area.

C There is no movement of charge.

D The conductor now becomes an insulator.

3 For any closed loop in an electrical circuit, the sum of the potential differences must be zero. This is otherwise known as:

A Kirchhoff's current law.

B Coulomb's law.

C Kirchhoff's voltage law.

D the law of conservation of charge.

4 Electrons are added to an area of an insulator. What is most likely to happen?

A Protons in the insulator move towards the area.

B Electrons in the insulator move away from the area.

C There is no movement of charge.

D The insulator will now attract electrons.

5 Determine the magnitude and direction of the current I in Figure 9.7.1.

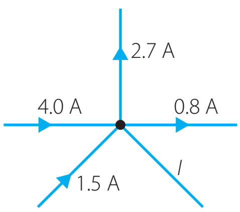

FIGURE 9.7.1

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6 V_2 in Figure 9.7.2 has a reading of 750 mV. What is the reading of V_1?

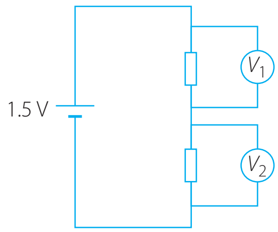

FIGURE 9.7.2

7 Towards which terminal (positive or negative) do electrons move when there is a potential difference applied across a wire?

8 Does conventional current describe the direction of flow of positive charge or negative charge?

9 How many electrons make 0.5 C of charge?

10 A circuit with EMF V, a resistor, R, and a total current, I, transforms energy, E, in a time interval, t. Write all the equations that show how power, P, is related to these variables.

11 A 100 W light globe is left on for 1.0 hour. How much energy is used by the globe? Give your answer in joules and kilowatt-hours.

12 Calculate the potential difference of a battery that supplies 4.5 J of energy to every 3.0 C of charge that passes through the cell.

13 Rose and Emilie are discussing an object with neutral charge. Rose says that a neutral object doesn't have any charge on it. Emilie says that a neutral object has lots of positive and negative charges on it, there are just equal numbers of each. Who is correct and why? Justify your response.

14 A current of 2.0 A flows in a battery when a light globe is connected across the terminals. The potential drop across the terminals is measured to be 6.0 V.

a What quantity of electric charge flows through the globe each second?

b How much energy is given to each coulomb of charge that passes through the battery?

c Determine how long it will take the battery to supply 480 J of energy.

15 A positively charged rod is moved near a neutral conducting rod. Do the two rods attract or repel? Use a diagram to explain.

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10 RESISTANCE

Introduction

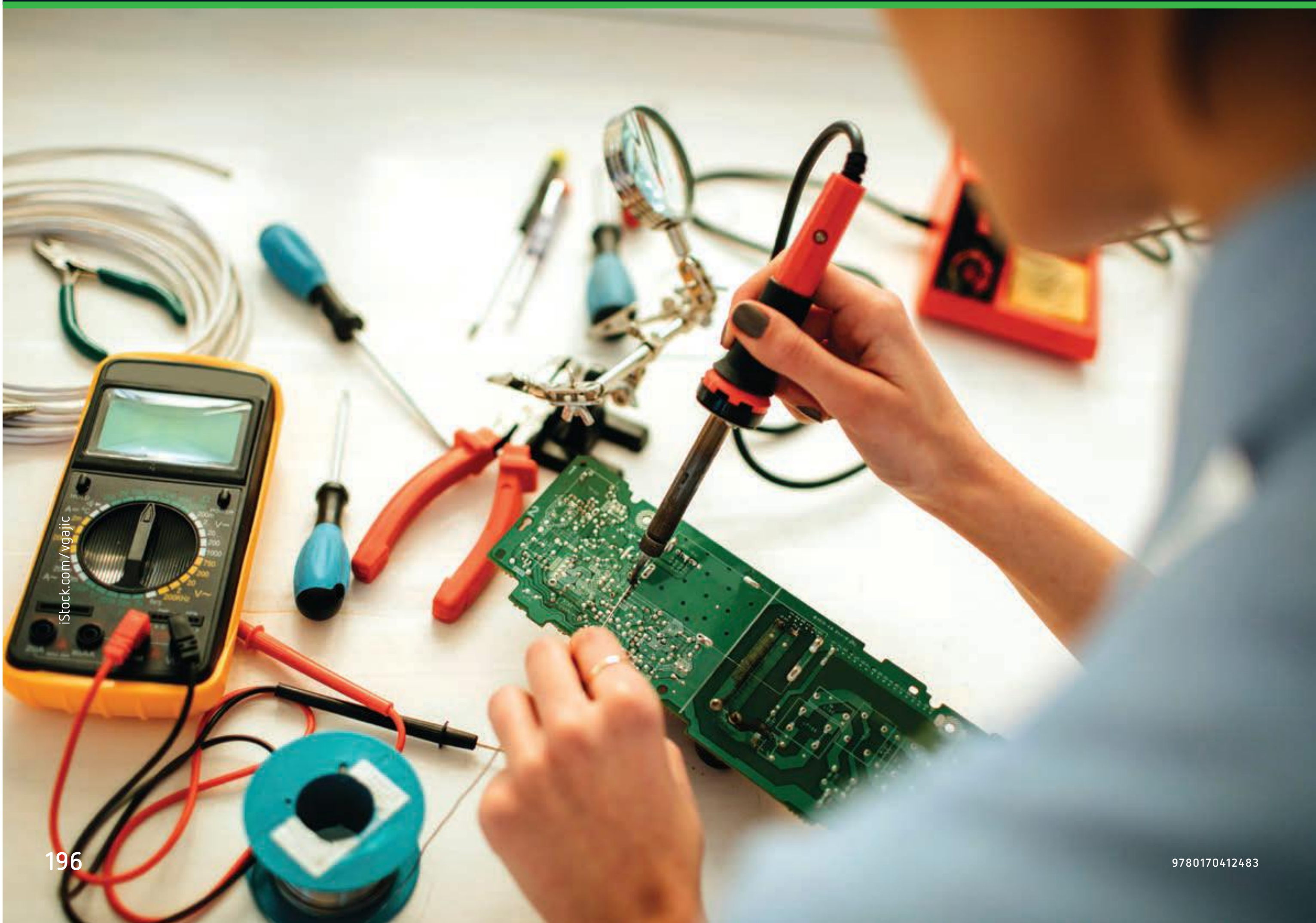
Electrons moving within a wire do not travel in a straight line, but rather they zigzag as they collide with the atoms in the wire, losing energy. This opposition to the flow of electric charge is termed resistance. In the case of older incandescent light bulbs, as the electrical energy passes through the filament of the bulb, it is converted into both useful light and wasted heat.

In this chapter the laws relating to resistance will be explained and applied to find the resistance within a range of common circuits and scenarios.

Stimulus questions

Why do some materials conduct electricity better than others?

Why are there laws phasing out the use of incandescent light bulbs?



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10.1 Resistance

When a potential difference is applied across a wire, the electrons tend to move from the negative terminal towards the positive terminal. This movement is not in a straight line; rather, the electrons zigzag as they collide with the atoms in the wire; that is, the wire resists the flow of charge. This deterrent to the flow of charge is termed **resistance**.

A material that allows current to flow through it easily is termed a **conductor**. Conductors are materials that have a large number of free or conduction electrons. These free electrons move from one area to another when there is a potential difference, making up the electric current. Metals are good examples of conductors as they have many free electrons and offer little resistance to the flow of charge. An **insulator** is a material that does not allow current to flow through it as it does not have free electrons. Plastics and ceramics are examples of good insulators. A **semiconductor** is a material with a very small number of free electrons at room temperature. A current can flow through a semiconductor, but not easily. Whether a material is a conductor, an insulator or a semiconductor depends on what sort of atoms it is made of, and how those atoms are bound to each other.

resistance
the opposition to the flow of electrical charge throughout a given material; it is measured in ohms, Ω, and is the ratio between potential difference and current

conductor
a material of low resistance that allows the flow of electrons; e.g. metals

insulator
a material that inhibits the flow of electrons; e.g. rubber

semiconductor
a material that conducts electricity less readily than a conductor but more than an insulator

resistivity, ρ
a measure of how much a material opposes the flow of charges; resistivity has the units Ωm

TABLE 10.1.1 Examples of conductors, insulators and semiconductors

Good conductors	Copper	Aluminium	Graphite
Poor conductors	Water	Human body	Sugar
Insulators	Glass	Rubber	Dry air
Semiconductors	Silicon	Germanium	Gallium

Some materials resist the movement of charge more than others. **Resistivity, ρ**, like resistance, refers to how much a material opposes the flow of charge. When you measure the resistivity of a substance you need to state the temperature at which it was measured. Temperature affects the conductivity of a material.

The resistance of a wire is affected by the cross-sectional area, A. As the thickness of the wire increases, the resistance decreases, as there are more conduction electrons in any length of the wire, hence $R \propto \frac{1}{A}$. As the length of the wire increases, the resistance also increases, as the charges have to collide with more atoms as they travel to the other end, hence $R \propto \ell$. This is summarised by the resistivity formula:

$$R = \rho \frac{\ell}{A}$$

where R = resistance (Ω), ρ = resistivity (Ω.m), ℓ = length (m) and A = cross-sectional area (m^2).

To calculate the resistance of a wire you need to know the resistivity of the material at a given temperature, the cross-sectional area of the wire and the length of the wire.

TABLE 10.1.2 Resistivity of some materials commonly used in electric circuits

MATERIAL	RESISTIVITY AT 20°C (Ω.m)
Copper	1.7×10^{-8}
Constantan	49×10^{-8}
Nichrome	1.1×10^{-6}
Carbon (graphite)	5.0×10^{-5}
Silicon	$0.1 - 6.0$

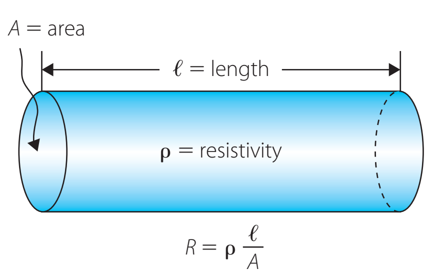

FIGURE 10.1.1 The resistance of a length of wire is dependent upon its resistivity, length and cross-sectional area.

10.1.1 Resistance in a wire

WORKED EXAMPLE 10.1.1

A wire has a cross-sectional area of 2.0 mm^2 and is 10.0 m long. If the resistance of the wire at room temperature is $1.1 \times 10^{-6}\,\Omega$, calculate the resistivity of the wire.

ANSWER

State the correct formula:

$$R = \rho \frac{\ell}{A}$$

Rearrange the formula to find ρ:

$$\rho = \frac{RA}{\ell}$$

List the known values and substitute into formula:

$R = 1.1 \times 10^{-6}\,\Omega$

$A = 2.0\,\text{mm}^2 = 2.0\,(\times 10^{-3}\,\text{m})^2 = 2.0 \times 10^{-6}\,\text{m}^2$

$\ell = 10.0\,\text{m}$

$$\rho = \frac{1.1 \times 10^{-6}\ \Omega \times 2.0 \times 10^{-6}\ \text{m}^2}{10.0\ \text{m}}$$

Calculate the answer:

$\rho = 2.2 \times 10^{-13}\,\Omega.\text{m}$

SCIENCE AS A HUMAN ENDEAVOUR

When Albert Einstein discovered the photoelectric effect in 1905, for which he won the Nobel Prize in Physics in 1921, he undoubtedly had little idea of the ramifications of this discovery for household and industrial lighting. Likewise, when Shuji Nakamura discovered how to make a blue light-emitting diode (LED), for which he won the Nobel Prize in Physics in 2014, he may not have known the wide-ranging implications of his research at the time. Similarly, the discovery of semiconductors has had a significant impact on the development of the personal computer, reducing computers from the size of a room to our current, wafer-thin tablets and phones. Further research and development in nanotechnology also has potential for applications in a number of fields. The significant global impact of such discoveries and their application to other areas of science, technology and engineering is evident.

Conduct research to investigate a scientific discovery, such as the photoelectric effect, the development of the LED, the development of semiconductors or nanotechnology (or a similar technology, in consultation with your teacher). Determine how the scientific discovery has been applied since its development, to illustrate how science understanding in one field can influence other areas of science, technology and engineering.

Resistor colour codes

Carbon resistors typically have four colour-coded bands on their cases. These bands are part of a code that allows you to determine their approximate resistance as well as their tolerance.

The fourth band is the tolerance band, which gives you an indication of the accuracy of the resistor. A gold band as the fourth band means a 5% accuracy, a silver band means 10% accuracy and no fourth band means 20% accuracy. The lower the percentage tolerance, the closer to its stated value and the more accurate the resistor will be.

To read the three other bands, place the tolerance band on the right and start from the left end. The first two bands form a two-digit number according to their colour (see Table 10.1.3). The third band is the multiplier and tells you how many zeros to put after the number, or more precisely, the index of the multiplier, $\times 10^n$.

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Reading a resistor colour code

1. Read the tolerance band. (As this is gold, the resistor has 5% accuracy.)
2. Read the colours of the first two bands to determine the digits. (The first band is blue, so it has a value of 6. The second band is red, so it has a value of 2. The digits are 62.)
3. Read the third band to determine the multiplier. (The third band is also red, so the multiplier is $\times 10^2$. The number is now 6200.)
4. Resistor values are always coded in ohms, so the value of this resistor is 6200 ohms or 6.2 kΩ.

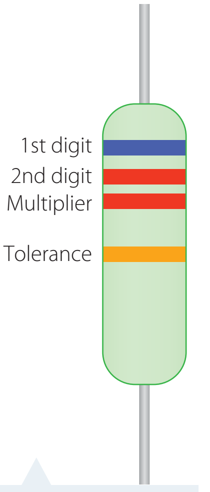

FIGURE 10.1.2 A colour-coded resistor

TABLE 10.1.3 Resistor colour codes

RESISTOR BAND COLOUR	DIGIT OR MULTIPLIER VALUE
Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet	7
Grey	8
White	9
Gold (tolerance)	± 5%
Silver (tolerance)	± 10%

Look at the resistors in Figure 10.1.3. Determine the values of these resistors, using the resistor colour codes in Table 10.1.3.

Many types of resistor are available. The resistance of carbon resistors is indicated by the coloured bands on their plastic casing.

FIGURE 10.1.3 Resistors have colour-coded bands on their cases.

SECTION REVIEW

10.1

REMEMBERING

1 List an example of:

- **a** a good conductor
- **b** a poor conductor
- **c** an insulator
- **d** a semiconductor.

2 State the formula for resistivity.

UNDERSTANDING

3 Explain why the resistance of a conductor is dependent upon its length.

4 Define 'resistance'.

APPLYING

5 A wire has a cross-sectional area of 0.5 mm^2 and is 2.0 m long. If the resistance of the wire is 50 mΩ, what is the resistivity of the wire?

6 A copper wire has a resistivity of 1.8×10^{-8} Ω.m. It has a length of 50 cm and a cross-sectional area of 1 mm^2. Calculate the resistance.

Ohm's law
the physical law that relates the current that flows through a conductor as directly proportional to the voltage across the conductor; that is, $\frac{V}{I}$ = a constant. The constant is termed the resistance of the conductor

potential difference, V
a measure of the potential energy per unit of charge. Potential difference and voltage are measured in volts (V); also termed voltage

current, I
the rate of flow of charge; that is, charge per unit time. It is measured in amperes, A

ohmic device
a component with constant resistance, i.e. a device that exhibits a proportional relationship between current and voltage: $R = \frac{V}{I}$

non-ohmic device
a component that does not provide a constant resistance: $R \neq \frac{V}{I}$

10.2 Ohm's law, ohmic and non-ohmic devices

Ohm's law

Resistance affects current and voltage. If a 12 V battery is placed in a circuit with a small resistance the current will be large. If a 12 V battery is placed in a circuit with a large resistance, the current will be smaller. **Ohm's law** describes the relationship between resistance, current and voltage. The resistance, R, of a circuit component is defined as the ratio of the **potential difference (V)** to the **current (I)**.

KEY FORMULA

$$R = \frac{V}{I}$$

Where:

Resistance, R, is measured in ohms (Ω), voltage, V, in volts (V) and current, I, in amps (A).

$$1.0\text{ ohm} = \frac{1.0\text{ V}}{1.0\text{ A}} = \frac{1\text{ volt}}{1\text{ ampere}} = 1\text{ V A}^{-1}$$

Ohmic and non-ohmic devices

A resistor is an electrical component that restricts the flow of current. In an **ohmic device** the resistance is constant for a wide range of voltages and currents. For ohmic resistors:

$$R = \frac{V}{I} = \text{constant}$$

This can be transposed to become:

$$V = IR$$

Current through an ohmic device is directly proportional to the potential difference across it. This is known as Ohm's law, and R is the constant resistance.

A characteristic current–voltage graph for an ohmic resistor is shown in Figure 10.2.1. The constant resistance of an ohmic device can be calculated as the inverse of the gradient.

In a **non-ohmic device**, the resistance of the device is not constant, hence the current–voltage graph for a non-ohmic resistor is non-linear (Figure 10.2.2). It is not a straight line as the resistance is not constant; the current does not vary proportionally with the voltage across the device.

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FIGURE 10.2.1 In an ohmic device the resistance remains constant as the voltage is proportional to the current. The resistance may be calculated at the inverse of the gradient.

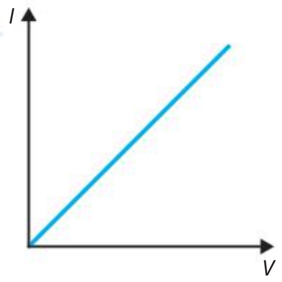
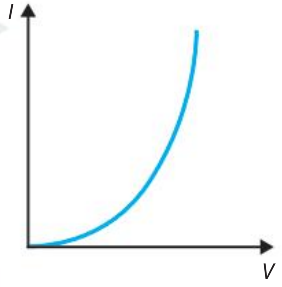


FIGURE 10.2.2 In a non-ohmic device the resistance is not constant. The voltage is not proportional to the current.



A number of different devices with non-constant resistance are used in electrical circuits. These include light globes, diodes, light-emitting diodes (LEDs), thermistors and light-dependent resistors (LDRs). The resistance of a non-ohmic device can be found; however, it will only hold true for the precise values for which it is determined. To calculate the resistance for a certain voltage, you can use the equation $R = \frac{V}{I}$.

10.2.1 Ohm's Law

10.2.2 Laws of nature: Ohm's Law

10.2.3 Ohm's Law and Resistance

WORKED EXAMPLE 10.2.1

The current–voltage graph for an ohmic resistor is shown in Figure 10.2.3. Calculate the resistance.

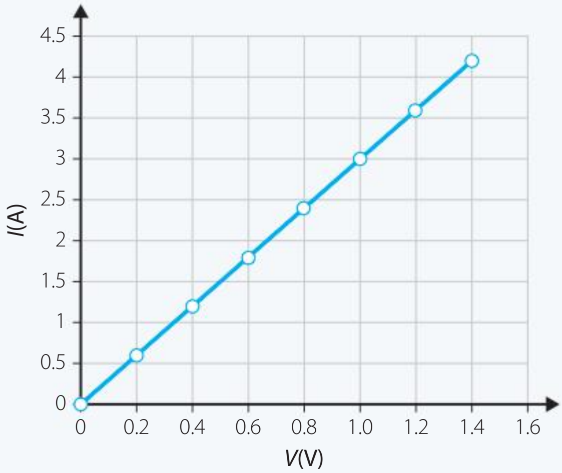


FIGURE 10.2.3

ANSWER

The gradient, m, represents the change in current with voltage:

$$m = \frac{\Delta I}{\Delta V} = \frac{1}{R}$$

Rearrange to make R the subject, then substitute known values:

$$\frac{1}{R} = \frac{y_2 - y_1}{x_2 - x_1}$$

$$\frac{1}{R} = \frac{3.0 - 0.0\ \text{A}}{1.0 - 0.0\ \text{V}}$$

Give the answer with the correct unit:

$R = 0.33\,\Omega$

WORKED EXAMPLE (10.2.2)

The current–voltage graph for a diode is shown in Figure 10.2.4. Calculate the resistance when there is a potential difference of 0.6 V across the diode.

ANSWER

Read the correct value from the graph:

At 0.6 V the current is 0.75 A.

State the correct formula, then substitute known values:

$R = \frac{V}{I}$

$R = \frac{0.6\text{ V}}{0.75\text{ A}}$

Give the answer with the correct unit:

$R = 0.8\,\Omega$

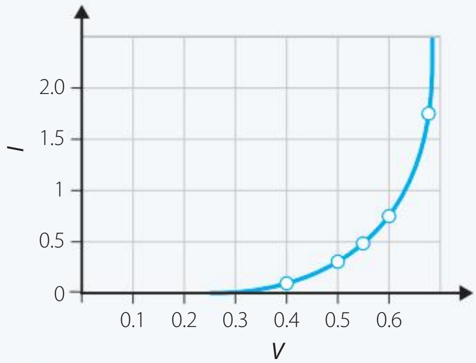


FIGURE 10.2.4

SECTION REVIEW 10.2

REMEMBERING

1 State Ohm's law.

2 List an example of an ohmic and a non-ohmic device.

UNDERSTANDING

3 Describe the difference between ohmic and non-ohmic materials.

APPLYING

4 Helen measured the current through an LED for five different potential differences. Her measurements are in the table.

Potential difference (V)	2.4	2.6	2.8	3	3.2
Current (mA)	0	1	4	12	25

a Plot the points on an I–V graph.

b Is this an ohmic or non-ohmic device? Explain your answer.

c What is the resistance when there is a potential difference of 3 V across the LED?

10.3 Interpreting graphs

When any conductor has a current passed through it, a voltage drop will occur due to the resistance of the conductor. For some materials, including metals, the drop in the voltage will be proportional to the current. This is what we now know as Ohm's law. As we have seen, this law is mathematically expressed as $R = \frac{V}{I}$. In a table of data of measured values, it is not necessarily immediately apparent whether this law is supported or not (i.e. whether a device is ohmic or non-ohmic). By graphing the data as a scatterplot and illustrating it visually, the relationship is seen more readily.

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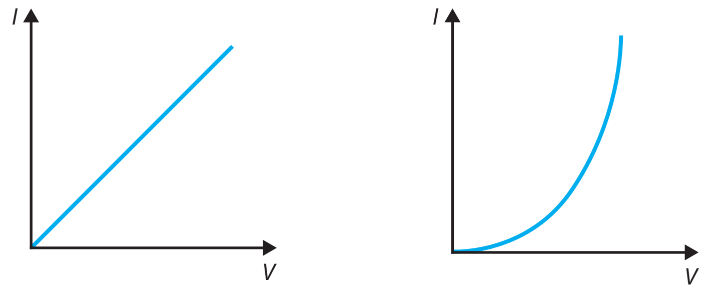


FIGURE 10.3.1 In ohmic devices the voltage is proportional to the current, as evidenced by a linear graph. In non-ohmic devices, the voltage is not proportional to the current, as evidenced by a non-linear curve.

random error also known as a two-sided error, presents as values above and below the expected values

systematic error also known as a one-sided error, presents as values that are either consistently above or consistently below expected values

When graphing experimental values, it is seldom that all data points line up exactly along a line of best fit. Of course, there is error associated with each measured value, hence we cannot expect all data to be perfectly precise, but how do we tell whether a set of values is precise enough? An experimental error is a difference between a measured value and an expected or theoretical value. Errors can occur in multiple ways, but are generally categorised as **random error** or **systematic error**. Common sources of random error include poor use of equipment and changes in the environment or surroundings while completing an experiment. Common sources of systematic error include incorrect calibration of a measurement device or not accounting for a zero error.

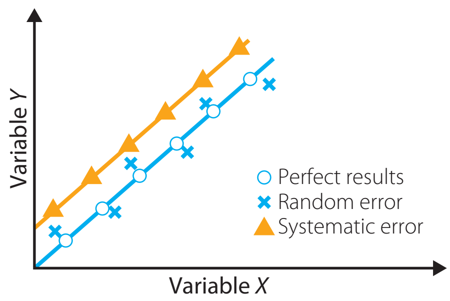


FIGURE 10.3.2 Experimental data is seldom perfect: usually there is one-sided error, two-sided error or both present in measured values.

In many instances the best method to present and to analyse data is to sketch a graph. Similarly, one of the most effective ways to represent errors or uncertainties is to use error bars. Error bars represent the uncertainty, by showing the lower and upper boundaries associated with each value. Rather than working out specific values for each point, it is often helpful to simply use the uncertainty of the worst (least precise) value for all points. The graph can be evaluated against the uncertainties of each value. A precise and representative line of best fit lies within the boundaries of each of the error bars.

SYLLABUS LINK

Chapter 2 discusses error in detail.

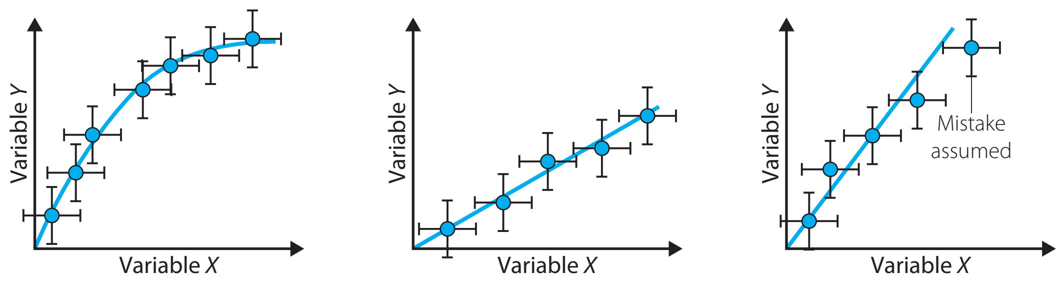


FIGURE 10.3.3 The line of best fit should lie within the boundaries of the error bars if the data is precise.

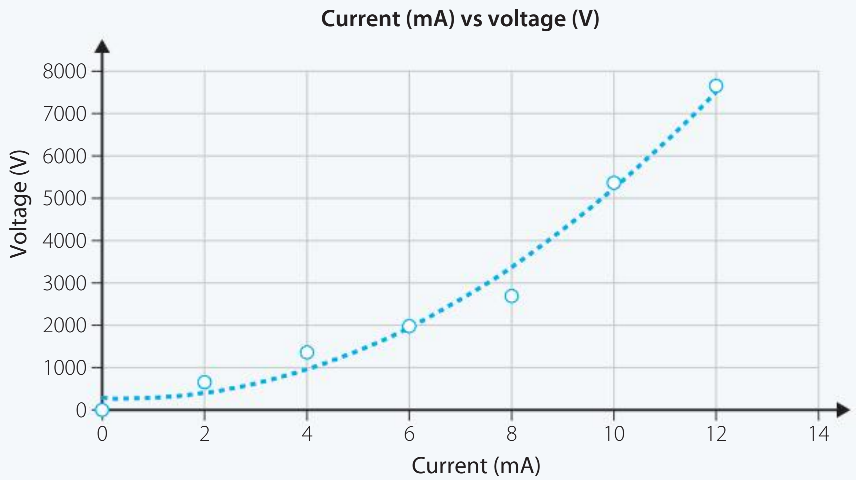
WORKED EXAMPLE 10.3.1

Current and voltage values were measured when investigating the properties of a fuse in an electrical circuit. The values are listed in the following table.

Voltage (V)	0	2	4	6	8	10	12
Current (mA)	0	660	1360	1980	2690	5370	7660

Graph the current and voltage values to determine whether the fuse is ohmic or non-ohmic. Give the graph a title and label the axes correctly. If it is ohmic, determine the resistance.

ANSWER



The current versus voltage graph does not appear to be linear, therefore the fuse is not ohmic over this range of values.

WORKED EXAMPLE 10.3.2

It is claimed a resistor has a resistance of 820 Ω ± 5% (i.e. 820 Ω ± 41 Ω). A student wishing to investigate this claim set up a circuit and measured the voltage across and current through the resistor for five different voltages. The current and voltage values are collated in the table below.

V_{820} (V) (±0.05 V)	4.91	3.84	3.01	2.12	0.53
I (A) (±0.0005 A)	0.0061	0.0047	0.0037	0.0026	0.0006

Graph the current and voltage values to determine whether the resistor is ohmic or non-ohmic. Give the graph a title and label the axes correctly. Note the uncertainty in each value and add the error bars to your graph. If the resistor is ohmic, determine the resistance and whether the experimental value is accurate.

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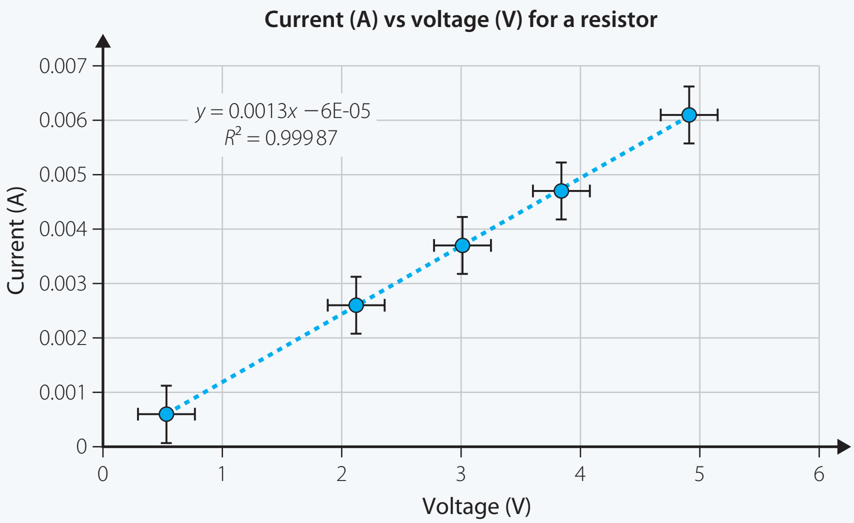
ANSWER



The current versus voltage graph appears linear, therefore the resistor is ohmic. The gradient of the graph represents $m = \frac{\Delta I}{\Delta V} = \frac{1}{R}$, hence the inverse of the gradient is the resistance:

$$m = 0.0013 \text{ A V}^{-1} = \frac{1}{R}$$

$$R = \frac{1}{0.0013}$$

Calculate the answer and state the unit:

$R = 769.2\,\Omega$

The line of best fit lies within the error bars of each value, hence it is precise.

The resistance value of $769.2\,\Omega$ lies outside the claimed tolerance of the resistor, as the lower boundary is equivalent to $820\,\Omega - 41\,\Omega = 779\,\Omega$; hence the data is inaccurate.

SECTION REVIEW 10.3

REMEMBERING

1 Give an example of a random error and a systematic error.

2 State the purpose of including error bars on a graph of experimental data.

UNDERSTANDING

3 Explain the difference between a random error and a systematic error.

ANALYSING

4 It is claimed a resistor has a resistance of $390\,\Omega \pm 5\%$. A student wishing to investigate this claim measured the voltage across and current through the resistor for five different voltages. The measurements were collated in the table below.

V_{390} (V) (± 0.05 V)	4.67	3.66	2.87	2.02	0.51
I (A) (± 0.0005 A)	0.012	0.009	0.007	0.005	0.001

a Graph the current and voltage values to determine whether the resistor is ohmic or non-ohmic. Give the graph a title and label the axes correctly.

b Note the uncertainty in each value and add the error bars to your graph.

c If the resistor is ohmic, determine the resistance and whether the experimental value is accurate.

10.4 Mandatory practical: comparing ohmic and non-ohmic resistors and determining the resistivity of a wire

PRACTICAL ACTIVITY 10.4.1

Comparing ohmic and non-ohmic resistors

Whether a resistor is ohmic or non-ohmic may be illustrated visually by measuring and graphing the current through and voltage across a device. If the relationship is constant, and produces a linear graph, then the resistor is termed ohmic. If it produces a non-linear curve, then the resistor is said to be non-ohmic.

AIM

To examine the relationship between the potential drop across each of three resistors connected in series and the current through them to determine whether they are ohmic or non-ohmic resistors

MATERIALS

- variable DC power supply (0 to 12 V)
- two different resistors
- a light-emitting diode (LED)
  (A simple electronics kit provides a range of resistors and LEDs)
- 2 multimeters (to measure voltage across and current through the circuit)

RISK ASSESSMENT

WHAT ARE THE RISKS IN DOING THIS EXPERIMENT?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
Electric shock is possible from faulty equipment.	Ensure that the power pack is not damaged and that it is connected correctly to the mains supply.
Resistors may become hot enough to burn.	Turn the power off when the circuit is not in use.

PROCEDURE

1 Connect the circuit as shown in Figure 10.4.1. Note that the longer leg of the LED must be connected to the positive terminal of the power pack.

2 With the DC supply set to 2 V, record the potential rise applied to the circuit across the power supply as well as the potential drop across resistor 1, resistor 2 and the LED. The multimeter should be used in parallel to measure the voltage across each. Record the measured values in a table like the results table that follows.

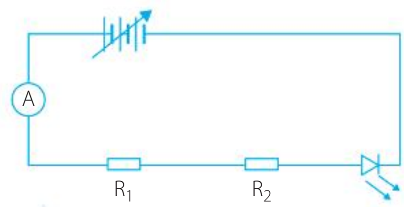


FIGURE 10.4.1 Experimental set-up for comparing ohmic and non-ohmic resistors

3 Still with the DC supply set to 2 V, record the current through the circuit. The multimeter should be used in series to measure the current. Record the measured values in your results table.

4 Repeat the procedure for DC settings of 4 V, 6 V, 8 V, 10 V and 12 V. Record the measured values in your results table.

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RESULTS

SUPPLY VOLTAGE (V)	VOLTAGE OF RESISTOR 1 (V)	VOLTAGE OF RESISTOR 2 (V)	VOLTAGE OF LED (V)	CURRENT (A)
2.0				
4.0				
6.0				
8.0				
10.0				
12.0				

ANALYSIS OF RESULTS

1 On one set of axes, plot a scatter graph of current, I, against voltage, V, for each of the three devices.
2 Add a line of best fit. Include the equation of the line and the R^2 correlation coefficient for any straight lines obtained.
3 Use the gradients of the lines and the relationship $m = \frac{\Delta I}{\Delta V} = \frac{1}{R}$ to determine the resistance of the devices that provided a straight line.

DISCUSSION

1 Why were at least five data points measured?
2 Were the measured values for voltage and current precise? (Refer to the correlation coefficient.)
3 List three sources of error in the measurements taken.
4 Which of these three devices is/are ohmic? Which is/are non-ohmic? Explain why.
5 For the ohmic devices, determine their resistance. (Show your calculation.)
6 For the ohmic devices, were their resistance values accurate? (Refer to the value of the resistor, if known.)

EXPERIMENT 10.4.2

Determining the resistivity of a wire

The resistance of a wire depends on the length (ℓ), cross-sectional area (A) and resistivity (ρ) of the wire. In this experiment you will determine the resistance of a wire for different lengths and thicknesses to allow you to calculate the resistivity of the wire.

AIM

To determine the resistivity of a wire

MATERIALS

- variable DC power supply (0 to 12 V)
- 2 m length of nichrome wire
- micrometer screw gauge
- tape measure

- 2 digital multimeters (to measure voltage and current, or resistance)
- 2 retort stands
- 2 G clamps

RISK ASSESSMENT

WHAT ARE THE RISKS IN DOING THIS EXPERIMENT?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
The wire can penetrate the skin if it is snapped.	Be careful not to overstretch the wire.
The wire may get hot when a current is passed through it.	Ensure that any current sent through the wire is kept low and that the power is turned off immediately after taking measurements.

PROCEDURE

1 Set up the materials as shown in Figure 10.4.2.

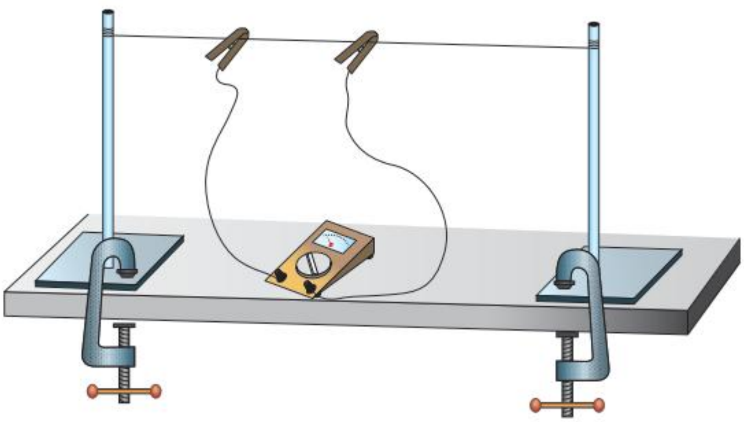

FIGURE 10.4.2 Experimental set-up for determining the resistivity of a wire

2 Tie 1 m of wire between the two retort stands, making sure that the wire is taut and without kinks.

3 Use the micrometer screw gauge to measure the thickness of the wire at three different points and calculate an average diameter. Use the diameter measurement to find the radius and then calculate the cross-sectional area of the wire.

4 Measure the resistance for a minimum of five different lengths of the wire. Record your measurements in a table similar to the results table below. (An alternative method for determining the resistance of the wire is to place a power pack set at 12 V across the wire and to measure the voltage across and current through five different lengths of the wire.)

RESULTS

LENGTH (m)	RESISTANCE (Ω)	VOLTAGE (V)	CURRENT (A)

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ANALYSIS OF RESULTS

Resistivity is given by the formula

$$\rho = \frac{RA}{\ell} \quad \text{or} \quad R = \frac{\rho \ell}{A}$$

where ρ is resistivity, measured in ohm metres, Ω.m; R is resistance, measured in ohms, Ω; A is cross-sectional area, measured in metres squared, m^2; and ℓ is length in metres, m.

1 Plot a scatter graph of resistance versus length with uncertainty bars.

2 Add a line of best fit. Include the equation of the line and the R^2 correlation coefficient.

3 Use the gradient of the line and the relationship $m = \frac{\Delta R}{\Delta \ell} = \frac{\rho}{A}$ to determine the resistivity of the nichrome wire. Multiply the gradient by the cross-sectional area to determine the resistivity. Estimate the uncertainty in this value.

DISCUSSION

1 Why were at least five data points measured?

2 Was the measured value for resistivity accurate? (Refer to Table 10.1.2, page 197, for values of the resistivity of some materials commonly used in electric circuits.)

3 Was the measured value for resistivity precise?

4 List three sources of error in the measurements taken.

5 Predict how differences in temperature may affect the results.

SECTION REVIEW 10.4

REMEMBERING

1 State the units for the following properties.

  a Resistance

  b Resistivity

  c Current

  d Voltage

2 Describe why a minimum of five data points are used to sketch a scatter plot.

UNDERSTANDING

3 State three different sources of error and explain a method to minimise each error.

4 Explain how you can test to determine whether a device is ohmic or non-ohmic.

CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 Define the following terms.
   a Resistance
   b Conductor
   c Insulator
   d Semiconductor

2 Show how the gradient of a current versus voltage graph can provide a value for resistance.

3 Explain the factors that may affect the resistance of a wire.

CATEGORY QUESTIONS

4 Contrast an ohmic device with a non-ohmic device.

5 Describe the measurements required to be able to determine the resistivity of a material.

6 List an example of a good conductor, a poor conductor, an insulator and a semiconductor. Describe the properties that differentiate these materials.

ELABORATION QUESTIONS

7 Explain why a random error may also be referred to as a two-sided error.

8 Predict the effects on current in a resistor if the temperature is decreased.

9 Define error bars on a scatterplot and explain their purpose on the graph.

EVIDENCE QUESTIONS

10 Perform research into superconductors and outline reasons for further investment into their development.

11 Identify the properties of gold and justify why gold is used in the circuits on computer chips.

12 Carbon and constantan (60% copper and 40% nickel) are commonly used as resistors. Perform research to identify other potential substances to use as resistors and describe the properties that make them suitable for this purpose

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END-OF-CHAPTER EXAM

End-of-chapter test

1 Resistance is best defined as:

- **A** the current through a conductor divided by voltage across it.
- **B** a value measured in Ω.m.
- **C** a quantity representing the opposition to the flow of electrical charge through a given material.
- **D** a measure of the amount of charge able to flow through a circuit in a given time.

2 The voltage across a 150 Ω resistor when 20 mA of current passes through it is calculated as:

- **A** 3 C
- **B** 30 V
- **C** 7500 V
- **D** 3 V

3 Two resistors are made of the same material. Resistor A is found to have a resistance of 220 Ω. Resistor B is found to have a resistance of 440 Ω. What is true about the relationship between resistor A and resistor B?

- **A** Resistor B is half as long as resistor A.
- **B** The area of resistor B is four times the area of resistor A.
- **C** The diameter of the wire in resistor B is twice that of resistor A.
- **D** Resistor B is twice the length of resistor A.

4 If a wire were to be stretched to twice its length, and half its cross-sectional area, its resistance would:

- **A** double.
- **B** halve.
- **C** increase by a factor of four.
- **D** decrease by a factor of four.

5 Identify one of the factors that affects the resistance of a material.

6 What is the name given to a material of low resistance that allows the flow of electrons?

7 A wire has a cross-sectional area of 0.5 mm^2 and is 2.0 m long. If the resistance of the wire is 50 Ω, determine the resistivity of the wire.

8 A copper wire has a resistivity of 1.8×10^{-8} Ω.m. It has a length of 50 cm and a cross-sectional area of 1 mm^2. Determine the resistance of the copper wire.

9 What is the difference between an ohmic and a non-ohmic resistor?

10 Why does resistance increase with greater cross-sectional area?

11 When a potential difference of 16 V is applied across the ends of a wire, the current flowing in the wire is 2.4 A. Assuming that the wire is ohmic, determine the resistance of the wire.

12 What is the potential difference across a 1.8 kΩ resistor in which a current of 240 mA flows?

13 Two wires A and B of the same material have resistances of 6.0 Ω and 12.0 Ω, respectively. The length of A is double the length of B.

a Determine the ratio of the diameter of wire A to the diameter of wire B.

b Determine the current in each wire if the two wires are connected in parallel across a 6.0 V battery.

14 It is claimed a resistor has a resistance of 390 Ω ± 5% (that is, 390 Ω ± 5% of 390 Ω). A student wishing to investigate this claim set up a circuit and measured the voltage across and current through the resistor for five different voltages. The measurements were collated in the table below.

V_{390} **(V) (± 0.5 V)**	2.37	1.87	1.43	1.02	0.26
I **(A) (± 0.0005 A)**	0.0061	0.0047	0.0037	0.0026	0.0006

Graph the current and voltage values to determine whether the resistor is ohmic or non-ohmic. Give the graph a title and label the axes correctly. Note the uncertainty in each value and add the error bars to your graph. If the resistor is ohmic, determine the resistance and whether the experimental value is accurate.

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11 CIRCUIT ANALYSIS AND DESIGN

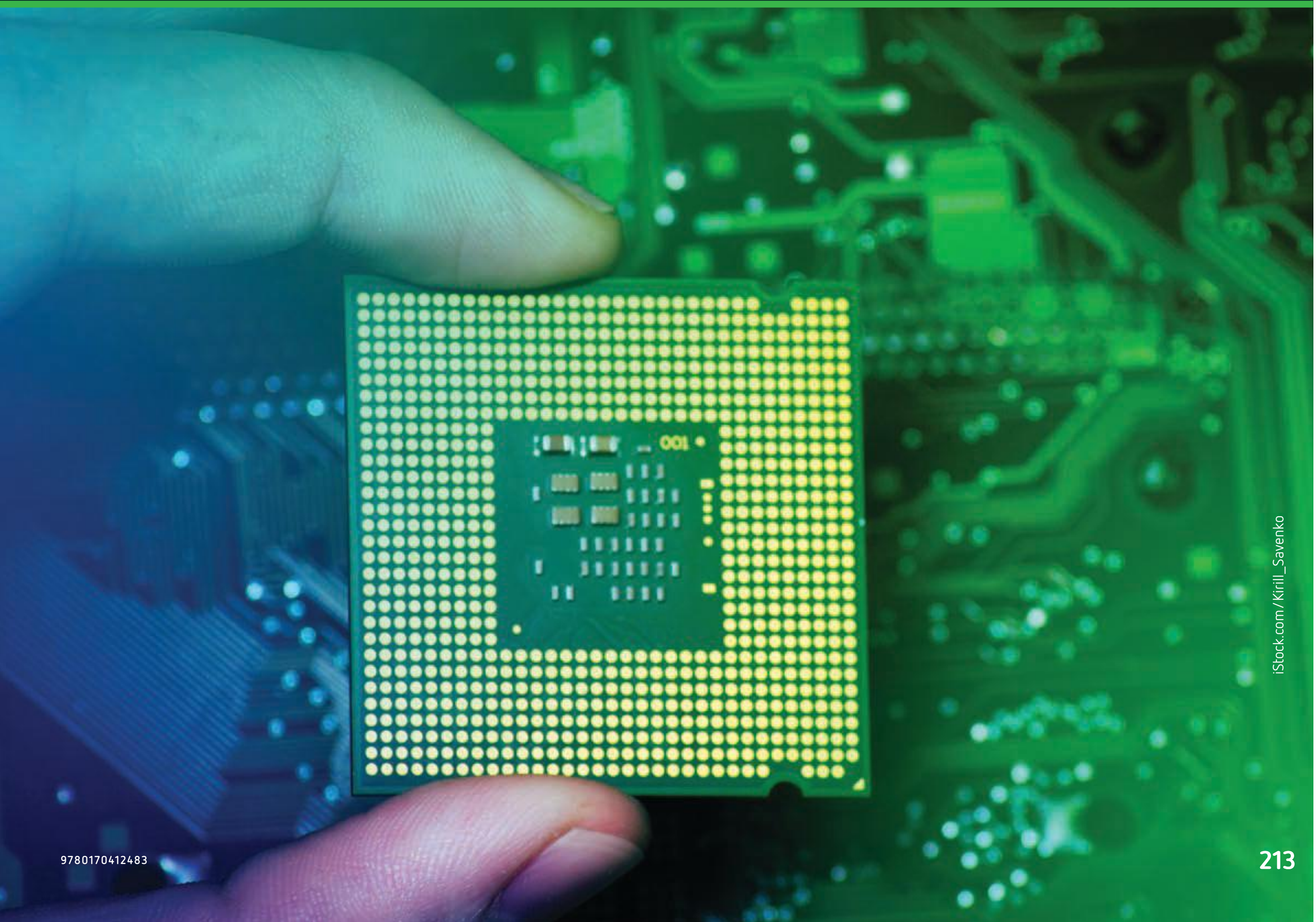
Introduction

The theory behind electricity can be applied in electronic circuits and the devices that we use every day. Electronics has revolutionised the way that we live. Computers and mobile phones look very different from those of a decade ago. Technology is continually making devices faster, 'smarter', smaller and more user friendly.

Stimulus questions

How are the circuits arranged in my house?

How much smaller can a computer get?



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11.1 Power dissipation

When electric charges run through an appliance, that appliance transforms energy over a given period of time. This is termed power dissipation. Given that the **potential difference** is a measure of the energy per unit of charge, and the **current** is a measure of the charge per unit of time, then the product of the potential difference and current provides a measure of the energy per unit of time. This is also known as **power**. This is shown mathematically below.

potential difference, V a measure of the potential energy per unit of charge. Potential difference and voltage are measured in volts (V); also termed voltage: $V = \frac{W}{q}$

current, I the rate of flow of charge; that is, charge per unit time. It is measured in amperes, A: $I = \frac{q}{t}$

power, P a measure of the rate of energy transformation. It is measured in watts, W

$$\text{Potential difference} \times \text{current} = \frac{\text{energy difference}}{\text{charge}} \times \frac{\text{charge}}{\text{time}}$$

$$= \frac{\text{energy difference}}{\text{time}} = \text{Power}$$

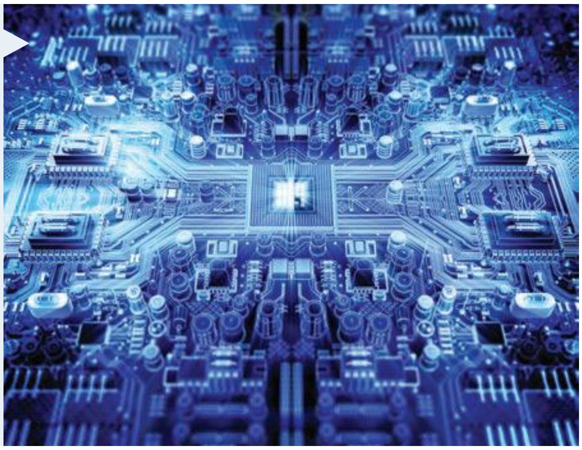

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FIGURE 11.1.1 As electronic circuits increase in complexity, they increase the capabilities of the electronic devices we use in daily life

KEY FORMULA

$$P = \frac{W}{t} = V \times I$$

Where:

V is measured in volts (V), I is measured in amperes (A), t is measured in seconds (s) and energy (W) is measured in joules (J). Power is then measured in watts (W).

1 watt = 1 W = 1 joule per second = $1\,\text{J}\,\text{s}^{-1}$

In an electrical circuit with a voltage supply and a resistor (load), such as Figure 11.1.2, energy is transformed and 'lost' as charge moves through the resistor. This energy difference per unit of time is the power dissipated by the resistor.

Depending on the measured values available, it is often useful to combine the formula for power, $P = V \times I$ with Ohm's law, $R = \frac{V}{I}$.

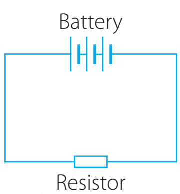

FIGURE 11.1.2 Power is dissipated as current passes through a device, such as a resistor.

KEY FORMULA

Ohm's law

$$R = \frac{V}{I}$$

Where:

Resistance, R, is measured in ohms (Ω), voltage, V, in volts (V) and current, I, in amps (A).

$$1.0\,\Omega = \frac{1.0\text{ V}}{1.0\text{ A}} = \frac{1\text{ volt}}{1\text{ ampere}} = 1\,\text{V}\,\text{A}^{-1}$$

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It is possible to deduce new relationships between power, voltage and current.
Since $P = V \times I$ and $V = I \times R$, then:

$$P = (I \times R) \times I$$

and

$$P = I^2 \times R$$

Similarly, if $P = V \times I$ and $V = I \times R$, then

$$P = V \times \frac{V}{R}$$

and

$$P = \frac{V^2}{R}$$

KEY FORMULA

Power, P

$$P = \frac{W}{t} = V \times I = I^2 \times R = \frac{V^2}{R}$$

Where:
V is measured in volts (V), I is measured in amperes (A), t is measured in seconds (s), energy (W) is measured in joules (J) and R is measured in ohms (Ω). Power is then measured in watts (W).

$1.0\ \text{W} = 1.0\ \text{J s}^{-1} = 1.0\ \text{V A} = 1.0\ \text{A}^2\,\Omega = \text{V}^2\,\Omega^{-1}$

WORKED EXAMPLE 11.1.1

A 1.4 kW electric toaster is plugged into the 240 V mains supply. Calculate:

a the current drawn.

b the resistance of the device.

c the power dissipated across the resistance of the toaster.

d the energy lost to heat energy if the toaster is used for 30 seconds.

ANSWERS

a
$$P = V \times I$$
$$I = \frac{P}{V}$$
$$I = \frac{1.4 \times 10^3\ \text{W}}{240\ \text{V}}$$
$$I = 5.83\ \text{A}$$

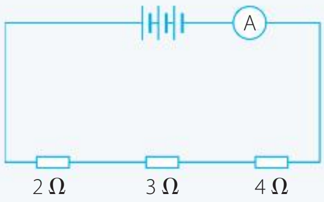
b
$$V = I \times R$$
$$R = \frac{V}{I}$$
$$R = \frac{240\ \text{V}}{5.83\ \text{A}}$$
$$R = 41.2\ \Omega$$

c
$$P = I^2 \times R$$
$$P = 5.83^2\ \text{A}^2 \times 41.2\ \Omega$$
$$P = 1400\ \text{W}$$

d
$$P = \frac{W}{t}$$
$$W = P \times t$$
$$W = 1400\ \text{W} \times 30\ \text{s}$$
$$W = 42\,000\ \text{J}$$
$$W = 42\ \text{kJ}$$

WORKED EXAMPLE 11.1.2

Determine the power dissipated across each of the resistors in the circuit below. The current measured through the circuit is 1.6 A.



ANSWER

$I = 1.6\text{ A}$

$P = I^2 \times R$

For the 2 Ω resistor:

$P = I^2 \times R$

$P = 1.6^2\text{ A}^2 \times 2\,\Omega$

$P = 5.12\text{ W}$

For the 3 Ω resistor:

$P = I^2 \times R$

$P = 1.6^2\text{ A}^2 \times 3\,\Omega$

$P = 7.68\text{ W}$

For the 4 Ω resistor:

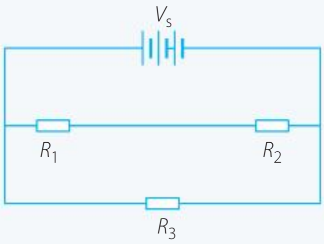
$P = I^2 \times R$

$P = 1.6^2\text{ A}^2 \times 4\,\Omega$

$P = 10.24\text{ W}$

WORKED EXAMPLE 11.1.3

An electrical circuit is set up with a voltage source of $V_S = 18\text{ V}$. The current splits between two parallel circuits, as shown. Determine the power dissipated across each of the resistors.
$R_1 = 60\,\Omega$, $R_2 = 90\,\Omega$ and $R_3 = 20\,\Omega$



ANSWER

$P = \frac{V^2}{R}$ and $P = I^2R$

For the R_1 and R_2 loop, $I = \frac{V}{R}$:

$I = \frac{18\text{ V}}{(60+90)\,\Omega}$

$I = \frac{18\text{ V}}{150\,\Omega}$

$I = 0.12\text{ A}$

For the $R_1 = 60\,\Omega$ resistor:

$P = I^2 \times R$

$P = 0.12^2 \times 60$

$P = 0.86\text{ W}$

For the $R_2 = 90\,\Omega$. resistor:

$P = I^2 \times R$

$P = 0.12^2 \times 90$

$P = 1.30\text{ W}$

For the $R_3 = 20\,\Omega$. resistor:

$P = \frac{18^2}{20}$

$P = 16.2\text{ W}$

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SECTION REVIEW 11.1

REMEMBERING

1 Define 'power'.

2 Recall Ohm's law.

UNDERSTANDING

3 Show three different equations to calculate the power dissipated from a device.

4 Convert the values below.

a 0.13 A to mA

b 6 kW to W

c 0.3 MV to V

APPLYING

5 Determine the power dissipated across a 60 Ω resistor if the current measured through the circuit is 0.8 amps.

11.2 Solving problems: potential difference, current, resistance and power

WORKED EXAMPLE 11.2.1

A 0.8 kW electric kettle is plugged into the 240 V mains supply. Calculate:

a the current drawn

b the resistance of the device

c the power dissipated across the resistance of the kettle

d the energy lost to heat energy if the kettle is used for 150 seconds.

ANSWERS

a
$$P = V \times I$$
$$I = \frac{P}{V}$$
$$I = \frac{800\ \text{W}}{240\ \text{V}}$$
$$I = 3.33\ \text{A}$$

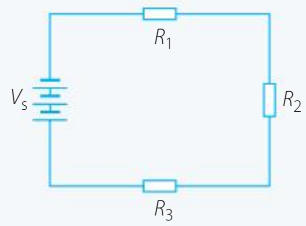
b
$$V = I \times R$$
$$R = \frac{V}{I}$$
$$R = \frac{240\ \text{V}}{3.33\ \text{A}}$$
$$R = 72.0\ \Omega$$

c
$$P = I^2 \times R$$
$$P = 3.33^2\ \text{A}^2 \times 72.0\ \Omega$$
$$P = 800\ \text{W}$$

d
$$E = P \times t$$
$$E = 800\ \text{W} \times 150\ \text{s}$$
$$E = 120\,000\ \text{J}$$
$$E = 120\ \text{kJ}$$

WORKED EXAMPLE 11.2.2

Determine the power dissipated across each of the resistors $R_1 = 18\,\Omega$, $R_2 = 12\,\Omega$ and $R_3 = 24\,\Omega$ in the circuit shown. The current measured through the circuit is 0.8 amps.



ANSWER

$P = I^2 \times R$

For the $R_1 = 18\,\Omega$ resistor:

$P = I^2 \times R$

$P = 0.8^2 \times 18\,\text{W}$

$P = 11.5\,\text{W}$

For the $R_2 = 12\,\Omega$ resistor:

$P = I^2 \times R$

$P = 0.8^2 \times 12\,\text{W}$

$P = 7.7\,\text{W}$

For the $R_3 = 24\,\Omega$ resistor:

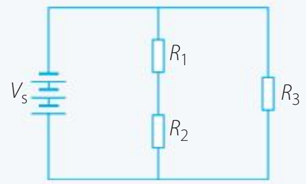
$P = I^2 \times R$

$P = 0.8^2 \times 24\,\text{W}$

$P = 15.4\,\text{W}$

WORKED EXAMPLE 11.2.3

An electrical circuit is set up with a voltage source of $V_S = 24\,\text{V}$. The current splits between two parallel circuits, as shown. Determine the power dissipated across each of the resistors $R_1 = 6\,\text{k}\Omega$, $R_2 = 9\,\text{k}\Omega$ and $R_3 = 4\,\text{k}\Omega$.



ANSWER

The voltage across R_1 and R_2 is shared in proportion with their resistances.

$$V_1 = 24 \times \frac{6000}{(6000 + 9000)}$$

$V_1 = 9.6\text{ V}$

$V_2 = 24\text{ V} - 9.6\text{ V}$

$V_2 = 14.4\text{ V}$

For the $R_1 = 6\,\text{k}\Omega$ resistor:

$$P = \frac{V^2}{R}$$

$$P = \frac{9.6^2\text{ V}^2}{6000\ \Omega}$$

$P = 0.0154\text{ W}$

For the $R_2 = 9\,\text{k}\Omega$ resistor:

$$P = \frac{V^2}{R}$$

$$P = \frac{14.4^2\text{ V}^2}{9000\ \Omega}$$

$P = 0.0230\text{ W}$

For the $R_3 = 4\,\text{k}\Omega$ resistor:

$$P = \frac{V^2}{R}$$

$$P = \frac{24^2\text{ V}^2}{4000\ \Omega}$$

$P = 0.144\text{ W}$

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SECTION REVIEW 11.2

APPLYING

1 An 800 W electric drill is plugged into the 240 V mains supply. Calculate:

- **a** the current drawn
- **b** the resistance of the device
- **c** the power dissipated by the use of the drill
- **d** the energy transformed if the drill is used for 20 minutes.

2 A 120 W set of electric beaters is connected to the 240 V mains supply and used for 6 minutes. Calculate:

- **a** the current drawn by the device
- **b** the resistance of the beaters
- **c** the power dissipated
- **d** the energy lost to other forms over the time the beaters were used.

ANALYSING

3 A 200 W electric hair straightener is plugged into the 240 V mains supply. Calculate:

- **a** the current drawn
- **b** the resistance of the device
- **c** the power dissipated from the heating element of the straightener
- **d** the energy lost to heat energy if the hair straightener is used for 8 minutes.

4 A 2.2 kW electric radiator is plugged into the 240 V mains supply. Calculate:

- **a** the current drawn
- **b** the resistance of the radiator
- **c** the power dissipated across the resistance of the radiator
- **d** the energy lost to heat energy if the radiator is used for 6 hours.

11.3 Electrical circuit symbols

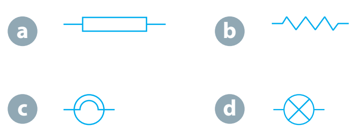
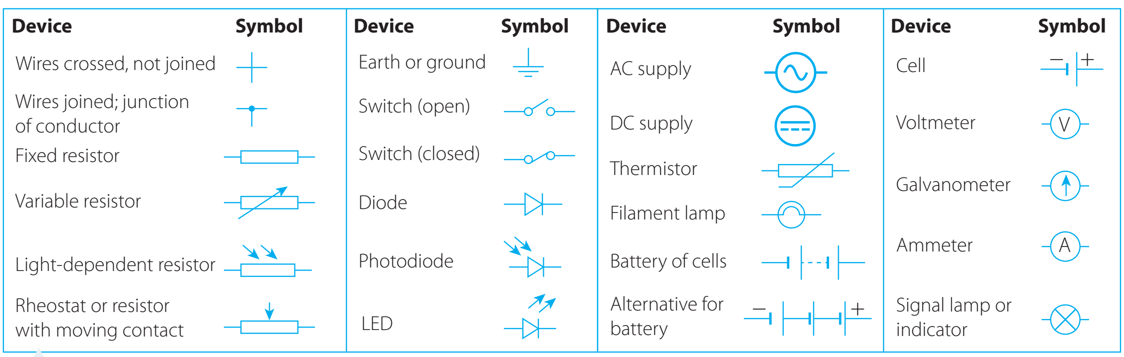


FIGURE 11.3.1 Some devices have alternate circuit symbols, such as the resistor (**a** and **b**) and the light globe (**c** and **d**). In each case, both forms are in accepted use.

Electrical circuits can be complex in their design. They are drawn using standard symbols to denote various devices and to show how they connect together. You should be able to recognise, draw and label a number of circuit symbols, including those for the resistor, voltmeter, ammeter, cell, battery, switch and lamp. Figure 11.3.2 displays many of the most recognisable and useful circuit symbols. Be aware that there are multiple symbols for some components, such as the resistor and the light globe.

11.3.1 Circuit symbols



Device	Symbol	Device	Symbol	Device	Symbol	Device	Symbol
Wires crossed, not joined		Earth or ground		AC supply		Cell	
Wires joined; junction of conductor		Switch (open)		DC supply		Voltmeter	
Fixed resistor		Switch (closed)		Thermistor		Galvanometer	
Variable resistor		Diode		Filament lamp		Ammeter	
Light-dependent resistor		Photodiode		Battery of cells			
Rheostat or resistor with moving contact		LED		Alternative for battery		Signal lamp or indicator	

FIGURE 11.3.2 Conventional symbols used in electrical circuit diagrams

WORKED EXAMPLE 11.3.1

Draw an electrical circuit with a battery of cells, a resistor and an open switch connected in series. Include an ammeter connected in series to measure the current through the circuit.

ANSWER

WORKED EXAMPLE 11.3.2

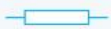
Draw and then label the following circuit symbols.

a 

b 

c 

d 

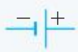
e 

ANSWERS

a 

Voltmeter

b 
Light globe

c 

Cell

d 
Alternating current (AC) supply

e 
Resistor (fixed)

SECTION REVIEW 11.3

REMEMBERING

1 Draw the electrical circuit symbols for the following devices.
- **a** Ammeter
- **b** Voltmeter
- **c** Cell
- **d** Variable resistor
- **e** Light globe

2 Identify two devices that have more than one accepted circuit symbol. Draw their symbols.

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11.4 Series, parallel and combination circuits

There are two main types of circuits. **Series circuits** have only one path through which the current can flow (Figure 11.4.1(a)). **Parallel circuits** have multiple paths through which current can flow (Figure 11.4.1(b)).

In a series circuit, the charged particles only have one pathway to go along. At each point in the path the flow of charge is the same. The current in Figure 11.4.1(a) is the same at points A, B and C. This is a consequence of the conservation of charge. The potential difference is shared between each of the circuit elements.

In a parallel circuit, such as in Figure 11.4.1(b), there are two or more pathways for the charged particles to travel along. At a junction, charges may go either way, splitting the current. The total number of charged particles that arrive at the junction each second is the same as the total number that leave the junction each second; that is, the current into a junction equals the current out of the junction. The potential difference is the same across parallel circuit elements.

series circuit
a circuit with only one path through which the current can flow

parallel circuit
a circuit with multiple paths through which current can flow

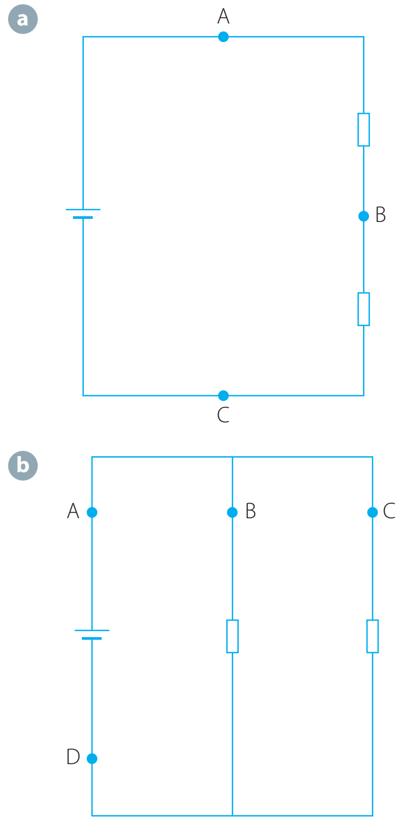


FIGURE 11.4.1 (**a**) A series circuit with two resistors; (**b**) a parallel circuit with two resistors

Resistors in series circuits

The potential energy per unit charge, or **EMF**, provided by a battery is used by the circuit elements. If there is one resistor in a circuit, then all the energy per unit charge, the potential difference, is applied across the resistor (Figure 11.4.2(a)). If two resistors are placed end to end in a series circuit (Figure 11.4.2(b)), the energy is shared between the two resistors. The current is the same in each resistor.

EMF
electromotive force; source of potential energy per charge, measured in volts, V

11.4.1 Resistors in series

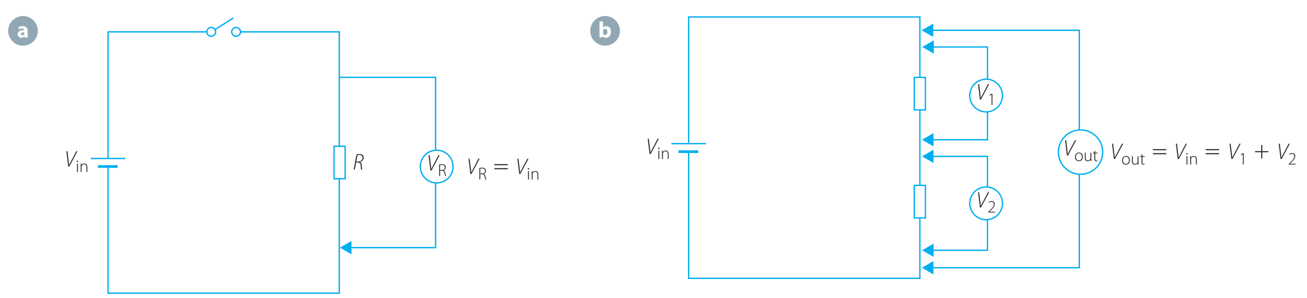


FIGURE 11.4.2 (**a**) A simple circuit comprising a source of EMF and one resistor. The potential difference across the resistor is the same as the potential difference across the source. (**b**) A series circuit comprising a potential source and two resistors in series. The sum of the potential differences across the resistors is the same as the potential difference across the source. The potential difference is shared between the resistors. The current is the same in the two resistors.

In a series circuit, the potential difference is shared:

$$V_T = V_1 + V_2$$

In a series circuit there are no junctions, so the current in each resistor is the same:

$$I_T = I_1 = I_2$$

Putting these together, we can deduce the equivalent resistance:

$$\frac{V_T}{I_T} = \frac{V_1}{I_1} + \frac{V_2}{I_2}$$

$$R_T = R_1 + R_2$$

KEY FORMULA

Any series circuit can be modelled by a single source and a single equivalent resistor.

KEY FORMULA

The equivalent resistance in a series circuit is the sum of all the resistances: $R_t = R_1 + R_2 + \ldots R_n$

Note that this result arises from the definition of resistance as the ratio of potential difference to current. It is applicable to all resistors connected in series.

Using Figure 11.4.2(b) (page 221), it can be seen that the ratio of the potential differences across each resistor is equal to the ratio of the resistances. The current is the same in each resistor, so:

$$I = \frac{V_1}{R_1} = \frac{V_2}{R_2}$$

$$\frac{V_2}{V_1} = \frac{R_2}{R_1}$$

This illustrates that the potential difference is divided in the ratio of the resistances.

WORKED EXAMPLE 11.4.1

Figure 11.4.3 shows an electrical circuit with two resistors in series.

a Draw a simplified circuit.

b Determine the total resistance of the circuit.

c Calculate the current in the circuit.

d Calculate the potential difference across:

i R_1

ii R_2

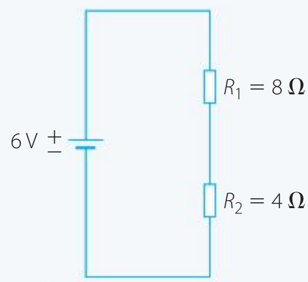
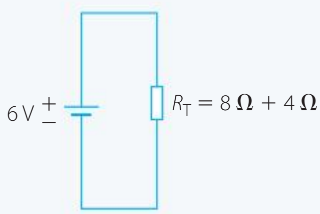


FIGURE 11.4.3

ANSWERS

a



b $R_T = R_1 + R_2$

$R_T = 8\,\Omega + 4\,\Omega$

$R_T = 12\,\Omega$

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c $R = \frac{V}{I}$

$I = \frac{V}{R}$

$I = \frac{6\ \text{V}}{12\ \Omega}$

$I = 0.5\ \text{A}$

d **i** $I = 0.5\ \text{A}, R = 8\ \Omega, V = ?$

$V_1 = I_1R_1$

$V_1 = 0.5\ \text{A} \times 8\ \Omega$

$V_1 = 4\ \text{V}$

ii $V_T = V_1 + V_2$

$V_2 = V_T - V_1$

$V_2 = 6\ \text{V} - 4\ \text{V}$

$V_2 = 2\ \text{V}$

Voltage dividers

A voltage divider is a simple series circuit in which part of the potential difference is used by each resistor. Sometimes the potential difference available from the power source is more than that required by the circuit. A **voltage divider**, or potential divider, takes advantage of the way a series circuit divides the potential difference between resistors.

voltage divider device used to vary voltage at the output depending on a control resistor; also called a potential divider

The simplest voltage divider uses two resistors. The potential drop across the two resistors adds to the same value as the supply voltage, V_{in}. In a voltage divider the output voltage, V_{out}, is the potential difference across *one* of the resistors and so is less than V_{in}. Use Ohm's law to calculate V_{out}.

$$R_T = R_1 + R_{out}$$

From Ohm's law (transposed):

$$I = \frac{V_{in}}{R_T}$$

$$I = \frac{V_{in}}{R_1 + R_{out}}$$

and

$$I = \frac{V_{out}}{R_{out}}$$

$$\frac{V_{in}}{R_1 + R_{out}} = \frac{V_{out}}{R_{out}}$$

$$\frac{V_{out}}{V_{in}} = \frac{R_{out}}{R_1 + R_{out}}$$

This is a ratio rule. The ratio of V_{out} to V_{in} is equal to the ratio of R_{out} to R_{total}.

11.4.2 Voltage dividers

WORKED EXAMPLE 11.4.2

For the circuit shown in Figure 11.4.4, calculate V_{out} if $V_{in} = 6.0\,V$, $R_1 = 1.0\,k\Omega$ and $R_{out} = 2.0\,k\Omega$.

ANSWER

$$\frac{V_{out}}{V_{in}} = \frac{R_{out}}{R_1 + R_{out}}$$

$$\frac{V_{out}}{6.0\ V} = \frac{2000\ \Omega}{1000\ \Omega + 2000\ \Omega}$$

$$\frac{V_{out}}{6.0\ V} = \frac{2000\ \Omega}{3000\ \Omega}$$

$$\frac{V_{out}}{6.0\ V} = \frac{2}{3}$$

$$V_{out} = \frac{2}{3} \times 6.0\ V$$

$$V_{out} = 4.0\ V$$

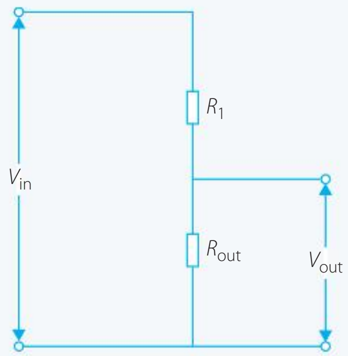

FIGURE 11.4.4

Resistors in parallel circuits

11.4.3 Resistors in circuits

The energy per charge provided by a battery, the EMF, is used by the circuit elements. If two resistors are placed side by side so that the current is shared, the elements are in parallel (Figure 11.4.5). Because the source of energy per charge is across both resistors, the two resistors use the same amount of energy per charge; that is, the energy per charge (potential difference) is the same across the two resistors. The current is shared between the resistors.

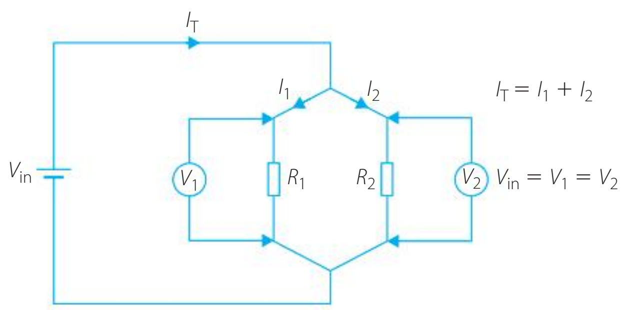

FIGURE 11.4.5 Resistors in parallel share the current and have the same potential difference.

KEY FORMULA

In parallel circuits, current is shared between circuit elements, such as resistors. Any parallel circuit can be modelled by a simpler circuit with a single source and a single equivalent resistor.

In a parallel circuit, the potential difference is the same across each resistor:

$$V_T = V_1 = V_2$$

In a parallel circuit, the total current in the circuit is shared between the resistors:

$$I_T = I_1 + I_2$$

From this the equivalent resistance can be deduced:

$$R = \frac{V}{I},\ I = \frac{V}{R}$$

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Thus: $I_T = I_1 + I_2$

becomes:
$$\frac{V_T}{R_T} = \frac{V_T}{R_1} + \frac{V_T}{R_2}$$

and
$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2}$$

Note that this result arises from the definition of resistance as the ratio of the potential difference to current. It is applicable to all resistors connected in parallel.

Using Figure 11.4.5, we can show that the ratio of the current in each resistor is equal to the inverse ratio of the resistances. The potential difference across each resistor is the same, so:

$$V = I_1R_1 = I_2R_2$$

$$\frac{I_1}{I_2} = \frac{R_2}{R_1}$$

KEY FORMULA

The equivalent resistance in a parallel circuit can be determined using the equation:

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots \frac{1}{R_n}$$

WORKED EXAMPLE 11.4.3

A circuit with two resistors in parallel is shown in Figure 11.4.6.

a Draw a simpler circuit.

b Determine the total resistance of the circuit.

c Calculate the current in the circuit.

d Calculate the current through each resistor.

  i R_1

  ii R_2

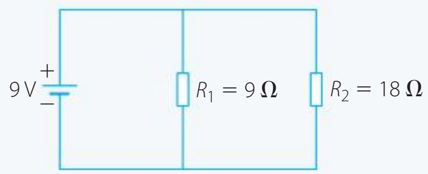
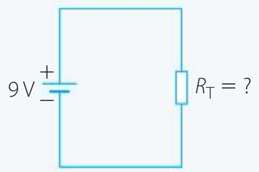


FIGURE 11.4.6

ANSWERS

a



b

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{9\,\Omega} + \frac{1}{18\,\Omega}$$

$$\frac{1}{R_T} = \frac{2}{18\,\Omega} + \frac{1}{18\,\Omega}$$

$$\frac{1}{R_T} = \frac{3}{18\,\Omega}$$

$$R_T = \frac{18\,\Omega}{3} = 6\,\Omega$$

c

$$R_T = \frac{V_T}{I_T}$$

$$I_T = \frac{V_T}{R_T}$$

$$I_T = \frac{9\text{ V}}{6\,\Omega} = 1.5\text{ A}$$

d **i** $V_T = V_1 = V_2$

$$I_1 = \frac{V_1}{R_1} = \frac{9\text{ V}}{9\,\Omega} = 1\text{ A}$$

ii $I_T = I_1 + I_2$

$I_2 = I_T - I_1 = 1.5 - 1.0 = 0.5\text{ A}$

PRACTICAL ACTIVITY 11.4.1

Investigating series and parallel circuits

In a series circuit there is a single path for the current to flow and in a parallel circuit there are multiple pathways. The type of circuit affects the way that the current and the voltage are distributed to the components.

AIM

To measure the change in current passing through light globes when connected in various series and parallel circuits. To measure the voltage across circuit components

MATERIALS

- variable DC power supply (0 to 12 V) set to 12 V
- 3 light globes rated to 12 V
- connecting wires
- 2 multimeters

RISK ASSESSMENT

WHAT ARE THE RISKS IN DOING THIS EXPERIMENT?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
There is a minimal risk of very small electric shock.	This risk can be managed by ensuring that the power pack is not damaged and that it is connected correctly.

PROCEDURE

1. Connect a series circuit with one globe as shown in Figure 11.4.7(a). Measure and record the current at each point marked in the circuit.
2. Connect a second globe in the series circuit as shown in Figure 11.4.7(b). Measure and record the current at each point marked in the circuit.
3. Connect a third globe in the series circuit as shown in Figure 11.4.7(c). Measure and record the current at each point marked in the circuit.

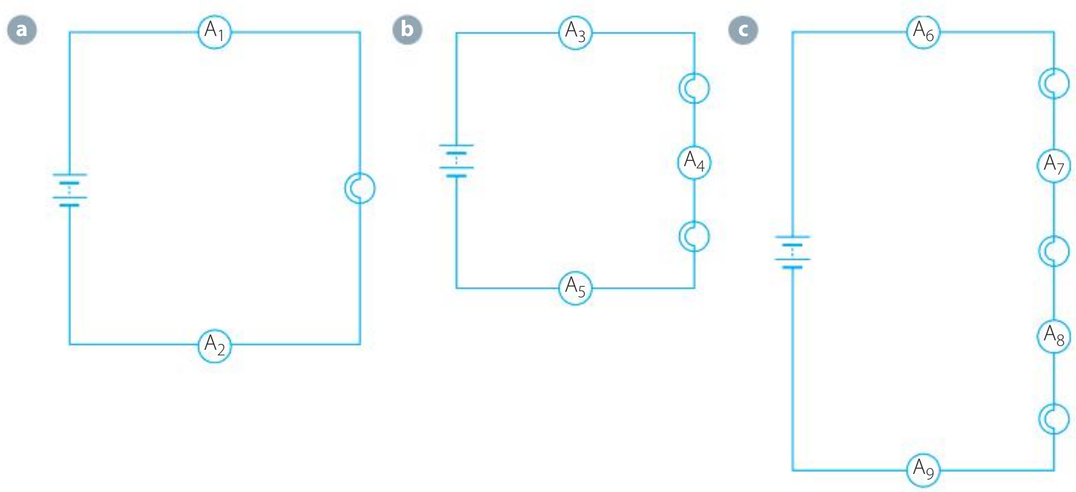


FIGURE 11.4.7 Series circuits for analysis

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4 Connect two globes in parallel as shown in Figure 11.4.8(a). Measure and record the current at each point marked in the circuit.

5 Connect three globes in parallel as shown in Figure 11.4.8(b). Measure and record the current at each point marked in the circuit.

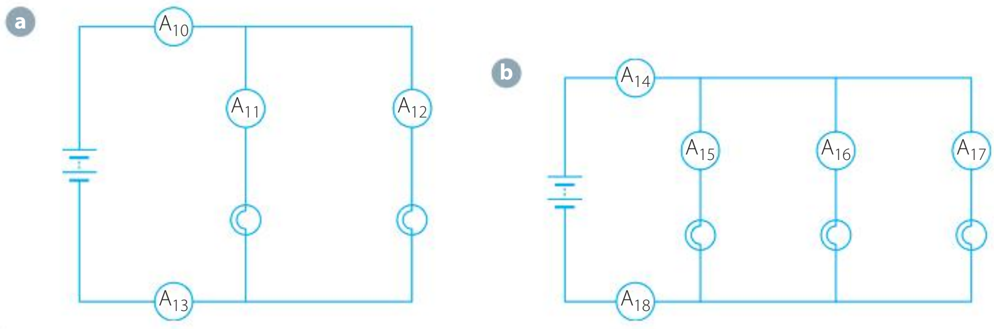


FIGURE 11.4.8 Parallel circuits for analysis

RESULTS

TABLE 11.4.1 Results for currents measured in series and parallel circuits

SERIES CIRCUIT	CURRENT
1 globe	$A_1 =$ $A_2 =$
2 globes	$A_3 =$ $A_4 =$ $A_5 =$
3 globes	$A_6 =$ $A_7 =$ $A_8 =$ $A_9 =$

PARALLEL CIRCUIT	CURRENT
2 globes	$A_{10} =$ $A_{11} =$ $A_{12} =$ $A_{13} =$
3 globes	$A_{14} =$ $A_{15} =$ $A_{16} =$ $A_{17} =$ $A_{18} =$

ANALYSIS OF RESULTS

Sketch a graph comparing the number of globes on the horizontal axis with the total current on the vertical axis for the series circuit.

DISCUSSION

1 State what happened to the current as the number of globes increased in the series circuit. Explain how this relates to the resistance.

2 State what happened to the relative brightness as the number of globes increased in the series circuit.

3 Contrast the current values measured in the three-globe series circuit with those of the three-globe parallel circuit. Explain how this relates to the energy of each electron passing through a light globe.

4 What conclusions can you draw regarding the aim of this experiment and your findings?

» EXTENSION

1 Connect three globes in a parallel circuit as shown in Figure 11.4.9(e). Measure and record the current at different points within the circuit.

2 Measure the potential difference across each globe for each of the five different circuits in Figure 11.4.9. What do you notice about the values?

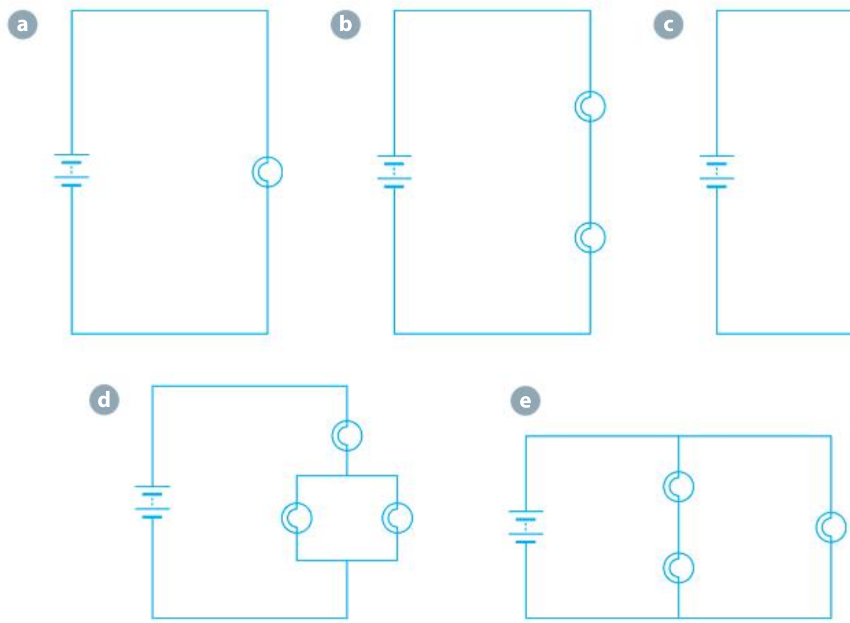


FIGURE 11.4.9 Further electrical circuits for analysis

Combination circuits

combination circuit
circuits that contain both series and parallel components

Combination circuits have both series and parallel components, as shown in the circuit in Figure 11.4.10. It is particularly useful to simplify the analysis of circuits by identifying equivalent resistances. Even complex circuits can be represented in a simpler form.

Table 11.4.2 summarises the difference between series and parallel circuits.

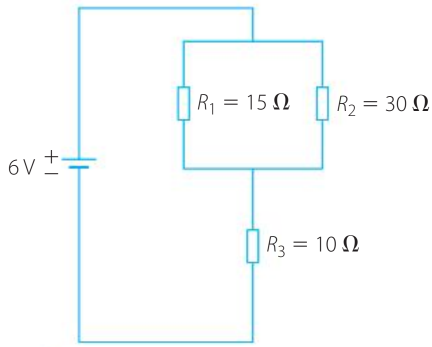


FIGURE 11.4.10 A combination circuit has both series and parallel components.

TABLE 11.4.2 Current and potential difference in series and parallel circuits

TYPE OF CIRCUIT:	CURRENT IN EACH CIRCUIT ELEMENT IS:	POTENTIAL DIFFERENCE ACROSS EACH ELEMENT IS:
series	same	shared
parallel	shared	same

Every circuit, even if it has several energy sources and several loads, can be represented by a simpler form to make it easier to analyse. A circuit can be modelled as one source of EMF that is the equivalent of all the sources, and one load that is the equivalent of all the loads.

KEY FORMULA

All circuits can be represented by a simpler arrangement of one equivalent source and one equivalent load.

SECTION REVIEW 11.4

REMEMBERING

1 State two other terms for the potential energy per unit of charge.

2 Complete the following statements to make them complete and correct.

a In a series circuit, the potential difference is ___________.

b In a series circuit there are no junctions, so the current in each resistor is ___________.

UNDERSTANDING

3 Contrast a series circuit with a parallel circuit.

4 State the rule for determining the total resistance in a series circuit.

5 State the rule for determining the total resistance in a parallel circuit.

APPLYING

6 Draw a circuit diagram with three 100 Ω resistors in series with a 60 V battery. Calculate the total resistance of the circuit and the current that would flow through the circuit.

7 Draw a circuit diagram with two 60 Ω resistors in parallel. Calculate the equivalent resistance and redraw the circuit so that it is simpler.

8 Draw a combination circuit that includes a 120 V AC supply, three 20 Ω resistors connected in parallel, and two light globes and a switch connected in series.

REFLECTING

9 Consider the steps involved in analysing circuits. Write down the main steps in order.

11.5 Circuit analysis

To analyse an electrical circuit, it is important to identify the energy source that is providing the potential difference, the components (or loads) that are transforming the energy, and the arrangement of the circuit (series or parallel, or combined). It is often useful to determine equivalent resistances for parallel components and to draw simpler equivalent circuit diagrams.

The application of Kirchhoff's current law, Kirchhoff's voltage law and Ohm's law is also required for effective analysis of circuits.

Care needs to be taken when applying Ohm's law, $V = IR$, to analyse combination circuits. It is important to work out which part of the circuit to apply the equation to, the whole circuit or just one component of the circuit.

Kirchhoff's current law (first law) the total current arriving at a junction within an electrical circuit is equal to the total current leaving the junction

Kirchhoff's voltage law (second law) for any closed loop in an electrical circuit, the sum of the potential differences must be zero

To use $V = IR$ on the whole circuit, you need to know the total resistance.

To use $V = IR$ on one component, you need to know the voltage drop and/or the current in that component.

When performing calculations using Ohm's law, use $V_T = I_T R_T$ for the whole circuit and use $V_n = I_n R_n$ for individual components.

Steps to analysing circuits

Analysing a combination circuit requires calculations based on the equivalent simplification of the circuit, to be able to specify the resistances, potential differences and currents of the components and of the whole circuit. A number of steps are involved in analysing a combination circuit.

Step 1: Determine which components are connected in series, and which are in parallel.

Step 2: Calculate the equivalent resistance across each parallel section.

Step 3: Simplify the circuit by redrawing it, replacing the parallel resistors with a single, equivalent resistor.

Step 4: Calculate the total current in the circuit using the total voltage and Ohm's law.

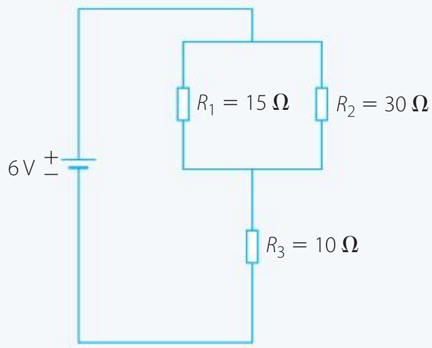
Step 5: Use Kirchhoff's current and voltage laws, as well as Ohm's law, to determine the current through and the voltage across all components.

Step 6: Calculate any power dissipations from the known values of current, voltage and resistance.

Step 7: Select a value/s to substitute back into the original problem to check your solutions.

WORKED EXAMPLE 11.5.1

The combination circuit shown in Figure 11.4.10 is redrawn as a simpler equivalent circuit here.



a Calculate the equivalent resistance of R_1 and R_2.

b Calculate the current in R_3.

c Draw one or more circuits to show the total resistance in the circuit as you proceed through the solution.

d Calculate the potential difference across R_3.

e Calculate the potential difference across R_1.

f Calculate the current in R_2.

ANSWERS

a
$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2}$$
$$\frac{1}{R_{eq}} = \frac{1}{15\ \Omega} + \frac{1}{30\ \Omega}$$
$$\frac{1}{R_{eq}} = \frac{2}{30\ \Omega} + \frac{1}{30\ \Omega}$$
$$\frac{1}{R_{eq}} = \frac{3}{30\ \Omega}$$
$$R_{eq} = 10\ \Omega$$

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b In R_3:

$$V_T = I_T R_T$$

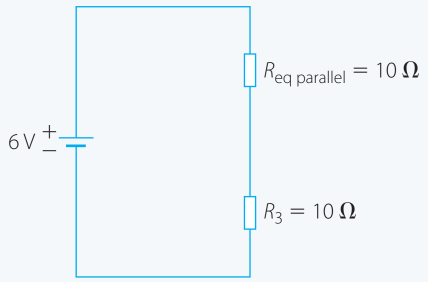
$$I_T = \frac{V_T}{R_T}$$

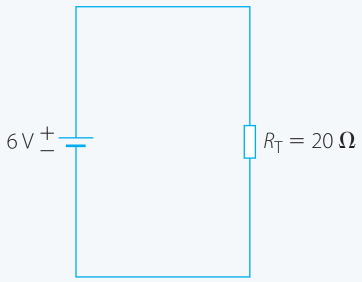
$$R_T = R_3 + R_{eq} = 10\,\Omega + 10\,\Omega$$

$$I_T = \frac{6.0\text{ V}}{20\,\Omega}$$

$$I_T = 0.3\text{ A}$$

c Draw a series circuit with the equivalent resistance for the parallel arrangement, then redraw the circuit showing the equivalent circuit for the series arrangement.





d $V_3 = I_3 R_3$

$V_3 = 0.3\text{ A} \times 10\,\Omega$

$V_3 = 3\text{ V}$

e $V_T = V_1 + V_3$

$V_1 = V_T - V_3$

$V_1 = 6\text{ V} - 3\text{ V}$

$V_1 = 3\text{ V}$

f $V_2 = I_2 R_2$

$$I_2 = \frac{V_2}{R_2}$$

$$I_2 = \frac{3\text{ V}}{30\,\Omega}$$

$$I_2 = 0.1\text{ A}$$

SECTION REVIEW 11.5

REMEMBERING

1 State Kirchhoff's current and voltage laws.

2 State Ohm's law.

UNDERSTANDING

3 Explain why care must be taken when applying Ohm's law to analyse combination circuits.

APPLYING

4 Find the total equivalent resistance of a circuit if four resistors of 40 Ω were connected:

- **a** in series
- **b** in parallel.

11.6 Solving further problems: circuit analysis

WORKED EXAMPLE 11.6.1

Find the total equivalent resistance of a circuit if three resistors of 200 Ω were connected:

a in series

b in parallel.

ANSWERS

a In series:

$R_T = 200\,\Omega + 200\,\Omega + 200\,\Omega$

$R_T = 600\,\Omega$

b In parallel:

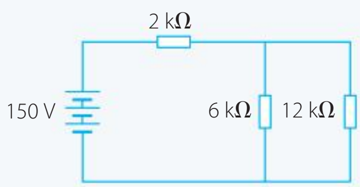
$$\frac{1}{R_T} = \frac{1}{200\,\Omega} + \frac{1}{200\,\Omega} + \frac{1}{200\,\Omega}$$

$$\frac{1}{R_T} = \frac{3}{200\,\Omega}$$

$$R_T = 66.67\,\Omega$$

WORKED EXAMPLE 11.6.2

Analyse the combination circuit shown by:



a calculating the equivalent total resistance of the circuit

b redrawing the circuit in a simpler form

c calculating the total current through the circuit

d calculating the potential drop across each resistor

e calculating the current through each resistor.

ANSWERS

a $R_T = 2\,\text{k}\Omega + R_{eq}$

To find R_{eq}:

$$\frac{1}{R_{eq}} = \frac{1}{6000\,\Omega} + \frac{1}{12\,000\,\Omega}$$

$$\frac{1}{R_{eq}} = \frac{3}{12\,000\,\Omega}$$

$$R_{eq} = 4000\,\Omega$$

$R_T = 2\,\text{k}\Omega + R_{eq}$

$R_T = 2\,\text{k}\Omega + 4\,\text{k}\Omega$

$R_T = 6\,\text{k}\Omega$

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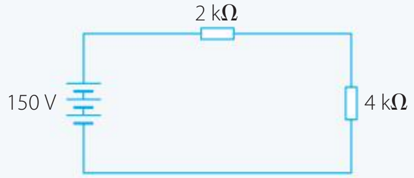
b Draw the simplified circuit.



c $V = I \times R$

$$I_T = \frac{V_T}{R_T}$$

$$I_T = \frac{150\ \text{V}}{6000\ \Omega}$$

$$I_2 = 0.025\ \text{A}$$

d The voltage drop across each resistor is found using Ohm's law, $V = I \times R$.

For the 2 kΩ resistor:

$V = 0.025\ \text{A} \times 2000\ \Omega$

$V = 50\ \text{V}$

For the 6 kΩ resistor:

$V = 150\ \text{V} - 50\ \text{V}$

$V = 100\ \text{V}$

For the 12 kΩ resistor:

$V = 150\ \text{V} - 50\ \text{V}$

$V = 100\ \text{V}$

e The total current running through the circuit, $I_T = 0.025\ \text{A}$, is the current running through the 2 kΩ resistor. According to Kirchhoff's current law, the total current is split between the paths through the 6 kΩ and 12 kΩ resistors unevenly, but with the same total current. Twice the amount of current will run through the 6 kΩ resistor than the 12 kΩ (as the 6 kΩ resistor has half the resistance).

The current through the 6 kΩ resistor is $\frac{2}{3} \times 0.025\ \text{A} = 0.0167\ \text{A}$

The current through the 12 kΩ resistor is $\frac{1}{3} \times 0.025\ \text{A} = 0.0083\ \text{A}$

WORKED EXAMPLE 11.6.3

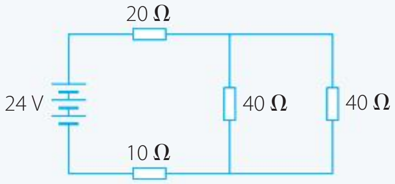
Analyse the combination circuit shown by:

a calculating the equivalent total resistance of the circuit

b redrawing the circuit in a simpler form

c calculating the total current through the circuit

d calculating the potential drop across each resistor.



ANSWERS

a $R_T = 20\,\Omega + R_{eq} + 10\,\Omega$

To find R_{eq}:

$$\frac{1}{R_{eq}} = \frac{1}{40\,\Omega} + \frac{1}{40\,\Omega}$$

$$\frac{1}{R_{eq}} = \frac{2}{40\,\Omega}$$

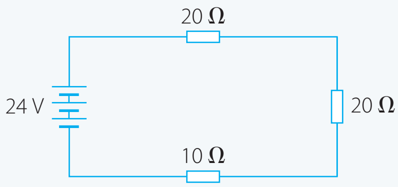
$$R_{eq} = 20\,\Omega$$

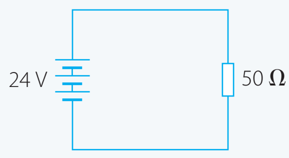
$$R_T = 20\,\Omega + R_{eq} + 10\,\Omega$$

$$R_T = 20\,\Omega + 20\,\Omega + 10\,\Omega$$

$$R_T = 50\,\Omega$$

b Draw the correct series circuit for the parallel arrangement, then redraw the circuit showing the equivalent circuit for the series arrangement.





c $V_T = I_T \times R_T$

$$I_T = \frac{V_T}{R_T}$$

$$I_T = \frac{24\ \text{V}}{50\,\Omega}$$

$$I_2 = 0.48\ \text{A}$$

d To determine the potential drop across each resistor we need to apply Ohm's law, being sure to use the current running through the individual path for that part of the circuit.

Voltage drop across the $20\,\Omega$ resistor:

$$V_{20\,\Omega} = I_{20\,\Omega} \times 20\,\Omega$$

$$V_{20\,\Omega} = 0.48\ \text{A} \times 20\,\Omega$$

$$V_{20\,\Omega} = 9.6\ \text{V}$$

Voltage drop across the $40\,\Omega$ resistors:

$$V_{40\,\Omega} = I_{40\,\Omega} \times 40\,\Omega$$

$$V_{40\,\Omega} = 0.24\ \text{A} \times 40\,\Omega$$

$$V_{40\,\Omega} = 9.6\ \text{V each}$$

Voltage drop across the $10\,\Omega$ resistor:

$$V_{10\,\Omega} = I_{10\,\Omega} \times 10\,\Omega$$

$$V_{10\,\Omega} = 0.48\ \text{A} \times 10\,\Omega$$

$$V_{10\,\Omega} = 4.8\ \text{V}$$

SECTION REVIEW 11.6

ANALYSING

1 Analyse the combination circuit in Figure 11.6.1 by:

- **a** calculating the equivalent total resistance of the circuit
- **b** redrawing the circuit in a simpler form
- **c** calculating the total current through the circuit
- **d** calculating the potential drop across each resistor
- **e** calculating the current through each resistor.

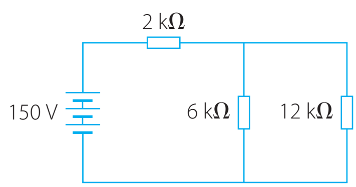


FIGURE 11.6.1

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2 Simplify the circuits in Figure 11.6.2 by finding their equivalent resistances, then redraw the circuits in simplified form.

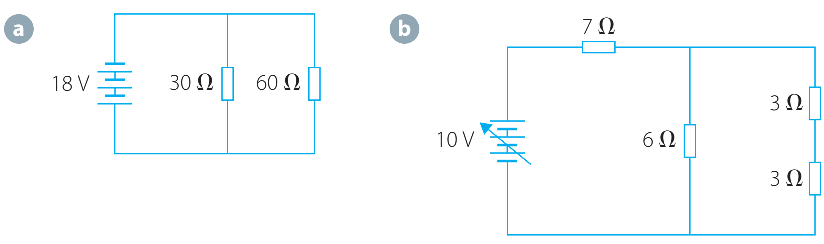


FIGURE 11.6.2

3 Analyse the combination circuit in Figure 11.6.3 by:

a calculating the equivalent total resistance of the circuit

b redrawing the circuit in a simpler form

c calculating the total current through the circuit

d calculating the potential drop across each resistor

e calculating the current through each resistor.

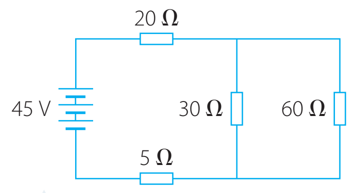


FIGURE 11.6.3

4 Analyse the combination circuit in Figure 11.6.4 to determine the values R_1 and V_T.

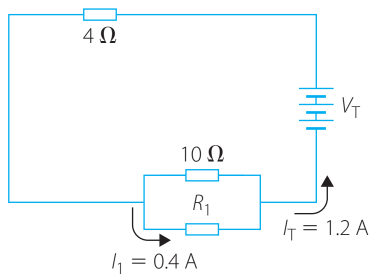


FIGURE 11.6.4

5 Analyse the combination circuit in Figure 11.6.5 to determine:

a the total equivalent resistance

b the total voltage supplied by the battery.

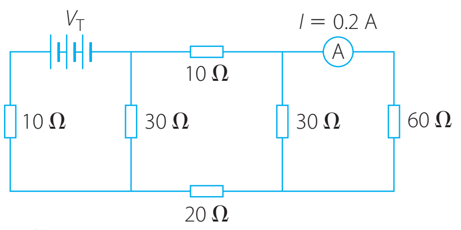


FIGURE 11.6.5

11.7 Designing circuits

Circuit design

An electrical circuit may contain many different electrical devices or components. Different circuits perform different roles, depending on whether their components are connected in series or in parallel – many circuits contain both arrangements. To design electrical circuits well, it helps to understand electrical wiring in the home.

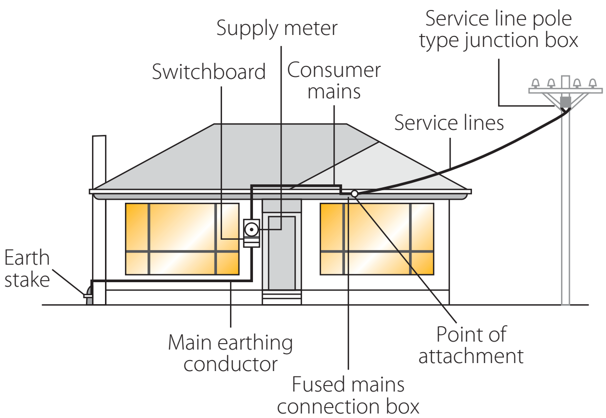


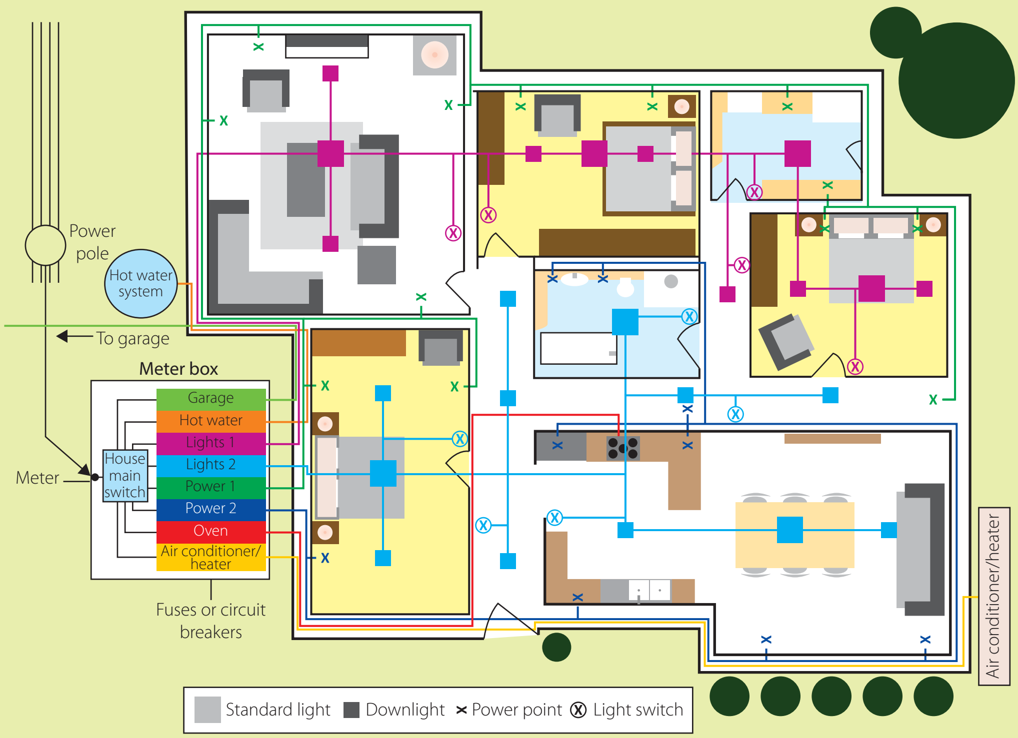
FIGURE 11.7.1 Typical household electrical supply system

Electricity in the home

The electricity supplied to houses in Australia is 240 V, 50 Hz single phase. There are two wires in the cable to the house – one is the active or phase wire and the other is the neutral wire. These come to a mains connection box that connects to the switchboard. The active lead is attached through an energy meter to the main switch and from there to a number of circuit breakers. The neutral wire is connected to a metal bar called the neutral bar, which is connected back to earth via a metal stake in the ground.

A typical electrical circuit diagram for a house can be seen in Figure 11.7.2. Each colour represents a circuit breaker within the switchboard. There are a number of separate circuits for lights, power points and larger appliances. The power points and lights are connected in parallel.

FIGURE 11.7.2 A typical electrical circuit diagram for a house



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Appliances are connected to the power point through a three-pin plug, or a two-pin plug if the appliance is double insulated. The active wire and the neutral wire connect to the circuit, which means that power can be supplied to the appliance. The earth wire is connected to the metal frame of the appliance so that if a fault develops it will trip the circuit breaker.

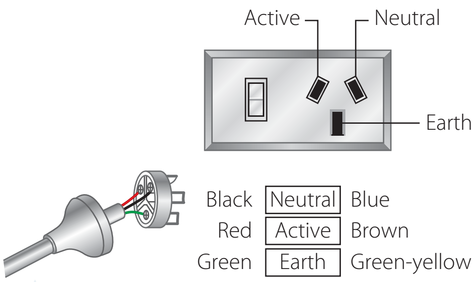

FIGURE 11.7.3 Colour code for a three-pin plug in a three-point power point

Short circuits and safety devices

A **short circuit** occurs when there is a current pathway between active and neutral connecting wires, so that the current is able to bypass the appliance and use a far less resistive pathway. The effect is that, with a much smaller resistance, the current through the circuit becomes much greater than when the circuit is in normal use. This brings into play the fuse or other safety, tripping device. A short circuit can occur, for example, when the insulation of two wires (active and neutral) in a cord wears through and the two bare wires touch each other. Alternatively, a bare active wire may touch a metal component on an appliance that is earthed. If a person touches a 'live' appliance, they may provide the conduction path to earth, which can end in a fatality.

A **residual current device (RCD)**, or earth-leakage protection, provides an extra safety feature to prevent electrocution. If a person touches a live wire and electricity flows through their body, then there will be an imbalance in the amount of current flowing through the active and neutral wires. If the imbalance reaches 50 mA then the RCD will break the circuit within milliseconds. The RCD is typically located in the main switchboard.

It is also important to protect circuits from power surges that can damage the wiring and appliances in the home. Circuit breakers and fuses are designed to break the circuit before damage is done. A fuse is a short piece of wire in the active circuit wire that will melt or 'blow' when the current through it exceeds a certain value. The **fuse** protects the circuit from an oversupply of current. Fuses for a domestic power supply are typically rated at 30 A for appliance circuits and 15 A for lighting circuits. A **circuit breaker** is an electromechanical device that automatically opens a switch if overload occurs. It contains an electromagnet that becomes more powerful as the current increases. When the current reaches a certain value, the electromagnet is powerful enough to force apart a contact and so break the circuit. It can do this in a very short time – less time than it takes for a piece of wire to burn through.

short circuit
connection between two points that allows current to flow with negligible resistance

residual current device (RCD)
earth-leakage protection device; safety protection against overload

fuse
temperature-dependent wire that melts if an overload occurs; safety protection against overload

circuit breaker
electromechanical switch that trips when there is an overload; safety protection against overload

PRACTICAL ACTIVITY 11.7.1

Designing and building simple circuits

In a series circuit there is a single path for the current to flow, while in parallel circuits there are multiple pathways. Combination circuits include both series and parallel components. The type of circuit affects the way that the current and the voltage are distributed to the components, and how they interact with one another.

AIM

To design and build simple electrical circuits
To model household circuits

MATERIALS

- variable DC power supply (0 to 12 V)
- 5 light globes rated to 12 V
- resistor
- variable resistor
- 12 V electric motor
- 12 V buzzer
- 6 switches
- connecting wires

RISK ASSESSMENT

WHAT ARE THE RISKS IN DOING THIS EXPERIMENT?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
There is a risk of electric shock and burns.	These risks can be managed by ensuring that the power pack is not damaged and that it is connected correctly to the mains power and that circuits are turned off when not specifically required to be in use.

SWITCH CIRCUITS

Switches are used to operate lights, fans and other electrical appliances every day. The switch performs the function of controlling the device by completing or disconnecting the electrical circuit. The switch has contacts that, when open, break the circuit. An open switch turns the circuit off, while a closed switch turns the circuit on.

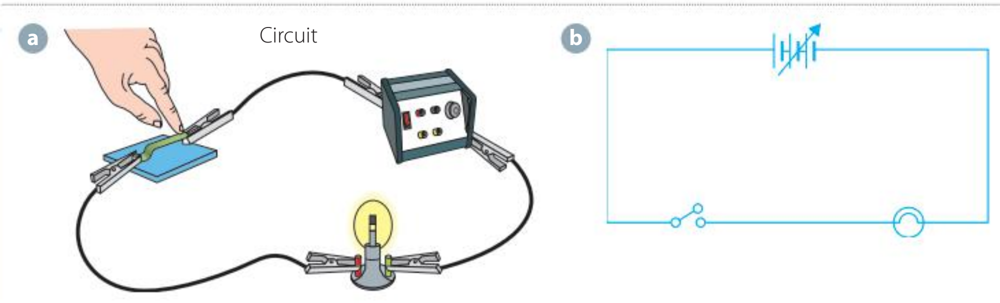

FIGURE 11.7.4 A simple switch circuit. When the switch is closed (on), the circuit is closed and the globe will glow. When the switch is open (off), the power supply to the globe will be shut off.

PROCEDURE 1

1. Connect a series circuit including a variable DC power supply, a light globe and a switch, as per Figure 11.7.4.
2. Turn the voltage supply to 2 V and close the switch. Note the brightness of the globe.
3. Turn the voltage up to 12 V, in 2 V increments, and note the brightness of the globe as the voltage increases through 4 V, 6 V, 8 V, 10 V and 12 V.
4. Record your observations.
5. Connect a motor or electric buzzer in series with the light globe in the circuit.
6. Turn the voltage supply to 12 V. Close the switch and observe the effect on the brightness of the globe.

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LIGHTS IN SERIES AND IN PARALLEL

In a typical household, lights, power points and appliances are connected in a variety of arrangements, though frequently they are placed in parallel circuits. This allows some appliances to be left on while others are off (using switches), as well as allowing remaining appliances to work when others have failed (e.g. a light globe blowing).

PROCEDURE 2

1. Connect a series circuit including a variable DC power supply, two light globes and a switch, as per Figure 11.7.5(a).
2. Turn on the voltage supply to 10V and close the switch. Note the brightness of the globes.
3. Remove one of the light globes from its mounting – this is replicating a blown light bulb.
4. Close the switch and record your observations.
5. Now connect a parallel circuit including a variable DC power supply, two light globes and a switch, as per Figure 11.7.5(b).
6. Repeat steps 2-4 for this circuit.

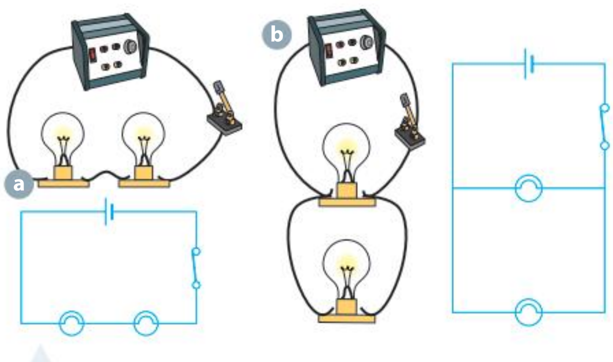

FIGURE 11.7.5 Light circuits in series and in parallel

HOUSEHOLD LIGHTING

At home, you are able to operate lights in each room independently – they don't necessarily all have to be on at once. Some lights you can dim.

PROCEDURE 3

1. Connect a combination circuit including a variable DC power supply, four light globes – two in series, two in separate parallel circuits, as per Figure 11.7.6.
2. Insert a switch within each parallel circuit.
3. Turn on the voltage supply to 10V. Close the switch on the parallel loop with two globes in series. Note the brightness of the globes.
4. Close the switch on a parallel circuit with one globe. Note the brightness of the globe.
5. Experiment with the switches for each parallel circuit, operating them independently and simultaneously. Note your observations.

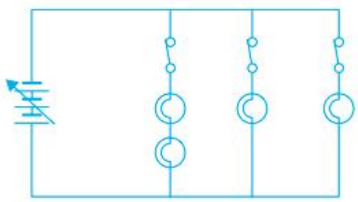

FIGURE 11.7.6 Light globes in series and in parallel circuits

MODEL HOUSE CIRCUITS

Houses, of course, have many more circuits than simply lighting circuits. To better replicate the electrical circuitry of a house we can construct a combination circuit with many more devices.

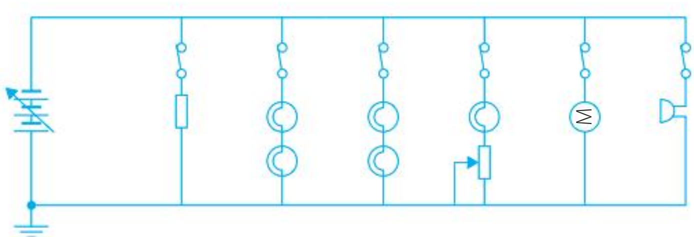

FIGURE 11.7.7 A model household combination circuit

» **PROCEDURE 4**

1. Connect a combination circuit including a variable DC power supply and five light globes in parallel circuits with switches, as per Figure 11.7.7 (page 239).
2. Connect a single resistor and switch in a parallel circuit. (The resistor represents a heater or toaster in the house.)
3. Connect a variable resistor (symbol) and switch in a parallel circuit with a light globe. (The variable resistor can be used as a dimmer switch for the lighting.)
4. Connect an electric motor (symbol –(M)–) and switch in a parallel circuit. (The motor represents an appliance, such as a dishwasher, fridge or fan.)
5. Connect an electric buzzer (symbol) and switch in a parallel circuit. (The buzzer represents a stereo.)
6. Connect a single connecting wire from the circuit to the benchtop. This represents the earth circuit.
7. Experiment with the switches for each parallel circuit, operating them independently and simultaneously. Note your observations.

EXTENSION

Create your own household circuit, incorporating different devices. Draw the circuit diagrams for each circuit.

RESULTS

Note your observations for each experimental procedure.

DISCUSSION

1. Compare your results and discuss your findings with your team members.
2. Compare the relative brightness of bulbs as the number of globes increases in a series circuit.
3. What can you conclude about the brightness of bulbs in parallel circuits?
4. What purpose do switches provide within electrical circuits?
5. What other electric appliances may be modelled with your components?

SECTION REVIEW 11.7

REMEMBERING

1. State the voltage and frequency of the mains power supply into Australian homes.

UNDERSTANDING

2. Describe the role of the residual current device, the circuit breaker and the fuse in a household electrical circuit. How are they similar and how do they differ?
3. Explain, with the use of a diagram, what a short circuit is.

APPLYING

4. Explain why there are several circuits for electric appliances within the home.

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CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 Define the following terms.
  a Potential difference
  b Current
  c Ohmic material
  d Power loss

2 Write two different formulas that can be used to determine the power dissipated across a device.

3 Explain the factors that affect the energy transformed by an electrical device.

CATEGORY QUESTIONS

4 Contrast the equivalent resistances of devices connected in series to those connected in parallel.

5 Explain why household lighting circuits are typically connected in parallel.

6 Draw an example of a series circuit, a parallel circuit and a combination circuit.

ELABORATION QUESTIONS

7 Explain how Kirchhoff's current law is a direct consequence of the conservation of electric charge.

8 Predict the effects on the power dissipated from a circuit if the current is decreased.

9 Explain how a short circuit can be created.

EVIDENCE QUESTIONS

10 Contrast the flow of charge in a series circuit and a parallel circuit. Use this to explain how Kirchhoff's voltage law is applied to parallel circuits.

11 A 1.0 kW electric blanket is plugged into the 240 V mains supply. Calculate the:
  a current drawn
  b resistance of the device
  c power dissipated across the resistance of the electric blanket
  d energy lost to heat energy if the electric blanket is used for 8 hours.

12 Find the total equivalent resistance of a circuit if three 15 Ω resistors are connected in:
  a series
  b parallel.

END-OF-CHAPTER EXAM

End-of-chapter test

1 Which of the following statements about series and parallel circuits is incorrect?

A The amount of current changes at different points of a series circuit.

B The potential energy changes at different points of a series circuit.

C The potential drop across any closed loop in a parallel circuit is equal to the supply potential.

D The current within a parallel circuit splits at junctions.

2 The correct units for the measured values of power, current, resistance and voltage, in order, are:

A ρ, A, Ω, mV.

B P, mA, kΩ, V.

C W, A, Ω, V.

D P, I, Ω, V.

3 Which statement regarding parallel circuits is incorrect?

A Parallel connections reduce the total resistance.

B Connecting components in parallel increase resistance.

C Circuits connected in parallel may use a switch to operate independently.

D Parallel circuits are preferred for household lighting circuits.

4 Which is a statement of Kirchhoff's current law?

A The total current in a parallel circuit remains the same throughout.

B For any closed loop in an electrical circuit, the sum of the potential differences must be zero.

C The total current arriving at a junction within an electrical circuit is equal to the total current leaving the junction.

D The total resistance within a series circuit is the sum of the individual resistances.

5 Draw the symbols for the following circuit devices.

A Ammeter

B Resistor

C Battery of cells

D Light globe

6 Whose law describes the relationship between resistance, voltage and current?

7 Which has less equivalent resistance: two 5.0 Ω resistors in series or two 5.0 Ω resistors in parallel? Compare the total current when connected to a battery of 20 V EMF.

8 State the formula for determining the equivalent resistance for resistors in parallel.

9 Define 'ohmic' and 'non-ohmic' resistors.

10 A 100 Ω resistor is placed in series with a parallel combination comprising a 200 Ω and a 500 Ω resistor. A 20 V DC power supply is connected across this combination circuit. Draw the circuit diagram and calculate the total resistance and voltage of the circuit as well as the current and voltages across each resistor.

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11 How does a short circuit occur?

12 Summarise the steps involved in analysing a combination circuit.

13 Four different combinations of resistors are shown in Figure 11.8.1. What is the total or equivalent resistance of each combination?

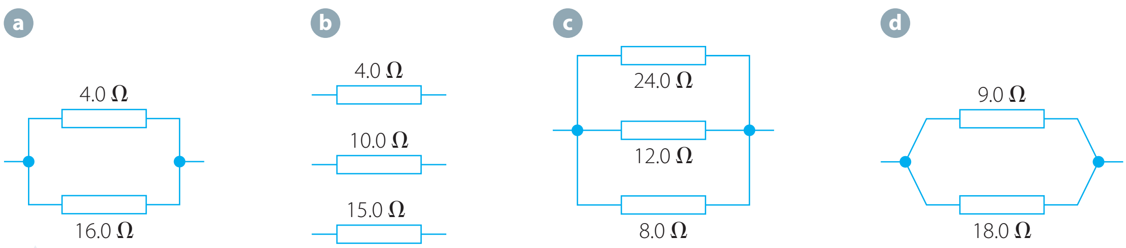

FIGURE 11.8.1

14 Two 12.0 Ω resistors and one 6.0 Ω resistor are connected in series across a 6.0 V battery.

- **a** Draw a circuit diagram to show this arrangement.
- **b** What is the total resistance of the circuit?
- **c** What current flows through the 6.0 Ω resistor?
- **d** What is the potential drop across each resistor?

15 Consider the combination circuit in Figure 11.8.2.

- **a** Calculate the current in R_3.
- **b** Draw one or more circuits to show the total resistance in the circuit as you proceed through the solution.
- **c** Calculate the potential difference across R_3.
- **d** Calculate the potential difference across R_1.
- **e** Calculate the current in R_2.

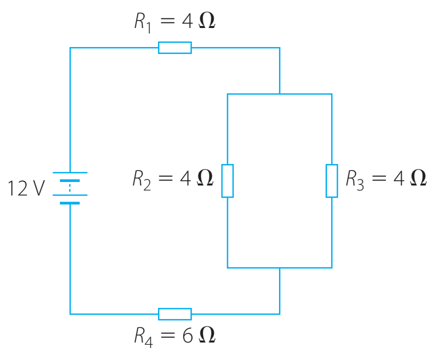

FIGURE 11.8.2

» UNIT TWO

LINEAR MOTION AND WAVES

- Topic 1: Linear motion and force
- Topic 2: Waves

Unit 2: Linear motion and waves provides a basis for student exploration of how physics is used to describe, explain and predict a wide range of phenomena. Understanding linear motion and the relationships between force, momentum and energy, as well as wave phenomena, will allow students to appreciate how physics applies in the engineering of structures and design of technologies, including accelerometers, fibre optics, lasers and car safety features. Student inquiry and analytic skills are developed through experimentation, investigation, worked examples, questions and activities that offer opportunities for interpretation, construction of algebraic, graphical and symbolic representation, and analysis of quantitative data and qualitative information.

UNIT OBJECTIVES

Students will:

1. describe and explain linear motion and force, and waves
2. apply understanding of linear motion and force, and waves
3. analyse evidence about linear motion and force, and waves
4. interpret evidence about linear motion and force, and waves
5. investigate phenomena associated with linear motion and force, and waves
6. evaluate processes, claims and conclusions about linear motion and force, and waves
7. communicate understandings, findings, arguments and conclusions about linear motion and force, and waves.

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» TOPIC 1

LINEAR MOTION AND WAVES

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Topic 1: Linear motion and force

The topic 'Linear motion and force' introduces students to vector quantities in one dimension, including the calculation of resultant vectors. Linear motion terminology is defined, including displacement, velocity and acceleration. Graphical representations of motion are interpreted and analysed by determining gradient, and areas under, the curves of displacement–time, velocity–time and acceleration–time graphs. Formulas are applied to solve problems involving uniformly accelerated motion. Concepts of energy, including kinetic and gravitational potential energy, the relationship between work and force, and elastic and inelastic collisions, are explored through solving problems and the interpretation of force–displacement and energy–time graphs. Practical skills, including the collection, linearisation and interpretation of motion data and the evaluation of experimental methodology, are addressed.

SCIENCE AS HUMAN ENDEAVOUR

Students should be given opportunities to investigate, using accelerometers and other motion detection systems: how an understanding of motion can contribute to car safety design and improvements in sports performance.

KEY FORMULAS

$$v = u + at$$

$$s = ut + \frac{1}{2}at^2$$

$$v^2 = u^2 + 2as$$

$$a_{net} = \frac{F_{net}}{m}$$

$$p = mv$$

$$\Sigma mv_{before} = \Sigma mv_{after}$$

$$W = \Delta E$$

$$W = Fs$$

$$E_k = \frac{1}{2}mv^2$$

$$\Delta E_p = mg\Delta h$$

$$\Sigma\frac{1}{2}mv^2_{before} = \Sigma\frac{1}{2}mv^2_{after}$$

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12 VECTORS

Introduction

The boundary of a T20 cricket pitch is 130 m in diameter. If you walk 55 m from the centre of the cricket pitch you can reach any point that is 10 m from the boundary line. This represents the distance you walked, but it does not say in which direction you walked. In this chapter you will consider the definition of, and differences between, quantities that have magnitude only (scalar) and those that have magnitude and direction (vector). You will also find out how to add and subtract vector quantities along a straight line.

Stimulus questions

If I stand in the middle of a field and I walk 55 m, where would I end up?

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12.1 Scalars and vectors

A **scalar** is a quantity that has only magnitude because it uses only one scale to represent the quantity. A person who walks 55 m from a fixed point could be anywhere on a circle of radius 55 m. This would be the distance walked. **Distance** is length, without specifying where the length is leading. Distance is a scalar quantity because it is only measured on a single scale. The scale is the length scale. Area (m^2) and volume (m^3) are also scalars because they are measured using only the length scale.

Some scalar quantities are shown in Table 12.1.1.

scalar
quantity specified by one measurement scale only, such as magnitude

distance
length

TABLE 12.1.1 Scalar quantities

QUANTITY AND USUAL SYMBOL	MEASUREMENT SCALE
mass, m	kilogram; kg
distance, d	metre; m
time, t	second; s
electric current, I	ampere; A
temperature, T	kelvin; K
luminous intensity, I	candela; cd
amount of substance, n	mole; mol
energy, E	joule; J

12.1.1 Scalars and vectors

12.1.2 Grid iron physics: scalars and vectors

12.1.3 What is a vector?

vector
quantity that has magnitude and direction; quantity characterised by two or more scales (from Greek 'to convey')

A **vector** quantity uses two or more measurement scales, for example magnitude and direction, in order to specify its full meaning. If we superimpose a compass on the 55 m walk, we can say how far and in what direction the person has walked (Figure 12.1.1).

The quantity that is specified by distance and direction from another point is the vector quantity **displacement**. Displacement is a vector quantity because it uses two scales; one to describe how far one position is away from another position (distance scale), the second to give the direction of the position relative to the other position (angle scale).

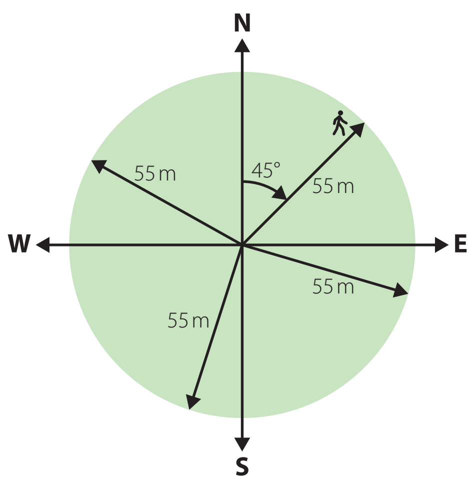

FIGURE 12.1.1 From the centre of the oval you can walk 55 m in any direction. The position is fixed when the compass direction is specified.

Representing vectors

Vector quantities are also represented in a variety of ways. Vectors will be shown in this book as a letter symbol, with an arrow on top: $\vec{A},\vec{B},\vec{C}$ etc. Vectors can also be represented as bolded and italicised letters (***A***, ***B***, ***C***, ***s***, ***v*** etc.) or letters capped with a tilde ($\tilde{A}$, $\tilde{B}$, $\tilde{C}$). Some vector quantities are shown in Table 12.1.2 (page 250).

The difference between a scalar quantity and a vector quantity is the number of measurement scales used. Scalars require one scale, vectors require two or more.

displacement
position relative to another position; the difference between two positions specified with respect to an origin

TABLE 12.1.2 Some vector quantities

QUANTITY AND USUAL SYMBOL	MEASUREMENT SCALES
displacement, $\vec{s}$	length; m and angle
velocity, $\vec{v}$	speed; m s^{-1} and angle
acceleration, $\vec{a}$	acceleration; m s^{-2} and angle
force, $\vec{F}$	magnitude of force; N and angle
momentum, $\vec{p}$	magnitude of momentum; kg m s^{-1} and angle

Angle measures

When a compass is used for direction, the angle is given as a bearing. Bearings can be stated as quadrant bearings or true (azimuth) bearings. Quadrant bearings use the angle, usually from the north or south direction, within the relevant quarter of the compass rose. Angles are then in the range from zero degrees to 90°. True or azimuth bearings take north as zero degrees and count 360° clockwise. For true bearings, east is 90°, south is 180° and west is 270°.

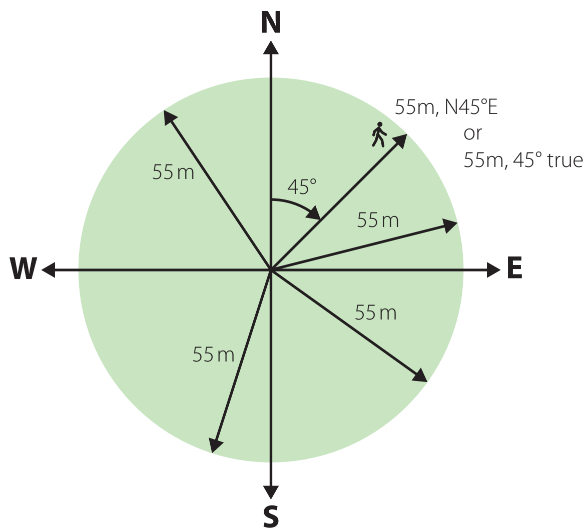

FIGURE 12.1.2 A person can walk a (scalar) distance to any point on the circle of radius 55 m. The (vector) displacement of the person shown is specified by distance (55 m) and direction (N45°E or 45° true).

Vector arrows

Vectors are represented by arrows. Arrows have tails and heads. The arrowheads point in the direction of the quantity. The length of the arrow is proportional to the magnitude of the quantity.

If you walk from the centre of the oval a distance of 33 m east, the vector would point east and the length would be 33 m on the scale used. If you then walk 44 m north, the vector would be proportionately longer. This path leads to a point that is 55 m from the centre and in the direction N37°E. Notice that the direct distance from the starting point to the finishing point is 55 m, not 33 m + 44 m = 77 m, which is the distance actually walked. Your final displacement is 55 m, N37°E (Figure 12.1.4).

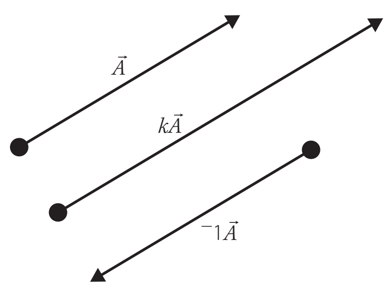

FIGURE 12.1.3 Vector arrows point from tail to head. Lengths can be changed by a scalar multiplier. Direction is reversed if the multiplier is negative.

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Scalar multiplication

A vector can be multiplied by a scalar. The multiplier changes the magnitude of the vector (Figure 12.1.3). We will see how vector multiplication applies to definitions of velocity and acceleration in Chapter 13, and to force and momentum in Chapter 14.

Division by a scalar is the same as multiplying by the inverse. If you multiply the magnitudes of the three vectors in Figure 12.1.4 by 1/11, which is the same as dividing the vector quantity by 11, the resultant triangle is the well-known 3, 4, 5 Pythagorean triangle.

If the multiplier is a negative value, the direction of the vector is reversed (Figure 12.1.3). If a north-pointing vector is multiplied by $^{-}1$, the new vector points south.

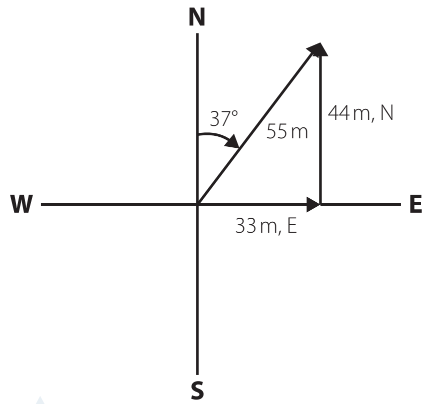

FIGURE 12.1.4 The distance travelled is 77 m but the displacement is 55 m, N37°E.

SECTION REVIEW 12.1

REMEMBERING

1 Define 'scalar', 'vector', 'distance' and 'displacement'.

2 Recall three quantities that are:
  a scalar
  b vector.

3 Describe the effect of multiplying a vector by:
  a a positive number
  b a negative number.

UNDERSTANDING

4 Identify one similarity and one difference between distance and displacement.

5 Explain why it is useful to distinguish between distance and displacement.

6 Identify one similarity and one difference between quadrant bearings and true or azimuth bearings.

APPLYING

7 Represent the following vectors as arrows with appropriate scales.
  a 10 m, N
  b 100 km, W
  c 25 cm, N45°E
  d 45 km, 225° true

ANALYSING

8 A person cycles 20 km east, then 20 km north, then 20 km west and comes to a stop after travelling 40 km south.
  a Draw the journey to scale.
  b Calculate the distance travelled.
  c State the final displacement.

9 When working with vectors explain why multiplication and division can both be treated as multiplication.

12.2 Movement along a straight line

Along a straight line, vector directions reduce to positive and negative. Number lines are most often drawn with the positive positions to the right of the origin and negative positions to the left. On such a number line, vectors can be added and subtracted algebraically.

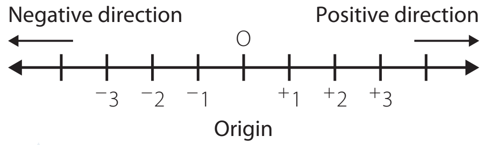

FIGURE 12.2.1 Number line showing origin and positive and negative directions

Displacement

The distance and direction between two positions is called the displacement. Along a straight line, the displacement vector for each position is either positive (to the right of the origin) or negative (to the left of the origin). Each position is at a positive or negative displacement relative to the origin. The displacement of one position on a number line relative to a second position is the difference between their positions: second position minus first position. A position on the number line is really the difference between the position and zero, the position of the origin.

KEY FORMULA

Along a number line, the displacement is the arithmetic difference between two positions, taking signs into account:

$$\vec{s} = \vec{d}_2 - \vec{d}_1$$

Where:

$\vec{d}_1$ = initial displacement from the origin

$\vec{d}_2$ = final displacement from the origin

$\vec{s}$ = displacement relative to the initial position

Displacement vectors may also be added to, or subtracted from, an original position displacement vector. For example, a person standing at a position of $^{+}5$ m from an origin can move a further distance of 2 m to a position either $^{+}7$ m from the origin (addition) or $^{+}3$ m from the origin (subtraction). Notice that in both cases the person has moved 2 m, but the final positions are different.

- Addition of a positive displacement means that a person at a position, such as $^{-}6$ or $^{+}4$, will move towards the right and become more positive (even if the result is still on the negative side of the origin). The addition of a positively directed displacement vector to any other displacement vector will always make the resultant vector more positive.
- Subtraction of a positive displacement is really the addition of a negative displacement. Thus, subtraction of a positive displacement means that, for example, a person at a position $^{-}8$ or $^{+}5$, will move towards the left and become less (or more) negative (even if the result is on the positive side of the origin). The subtraction of a positively directed displacement vector from another displacement vector will always make the resultant vector more negative.
- Subtraction of a negative displacement is the addition of the opposite displacement; that is, the addition of the opposite of negative, which is a positive. Thus, the subtraction of a negative displacement means that a person at a position, such as $^{-}10$ m or $^{+}2$ m, will move towards the right and become more positive. The subtraction of a negative displacement vector from another displacement vector will always make the resultant vector more positive.

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Distance

The distance travelled is different from the displacement. Distance is the magnitude of a displacement. If an object undergoes several position changes, the distance travelled is the sum of all the different displacements that make up the journey.

If the motion involves moving from the origin a distance d and back, the displacement is zero. The total distance travelled, however, is the sum of the distance of the outward displacement and the distance of the return displacement. Distance is, therefore, related to the *magnitudes* of the individual changes of position. It is the sum of the magnitudes of the individual displacements.

The magnitude of a displacement is the distance. We represent the magnitude by the modulus sign, $|\ldots|$.

KEY FORMULA

For any one displacement from position 1 to position 2, the distance is given by the magnitude of the vector displacement:

$d = |\vec{d}_2 - \vec{d}_1|$

- The distance of a journey is the sum of all the distances.
- In practice, this process is quite straightforward; trace the movement backwards and forwards along the number line and keep count of the individual distances moved.

WORKED EXAMPLE 12.2.1

An object moves from the origin to position P at $^{+}2\,\text{m}$ and then to the position Q at $^{+}5\,\text{m}$. Show working to calculate:

a the distance from the origin to P

b the distance from the origin to Q

c the distance between P and Q

d the displacement of Q relative to P

e the displacement of P relative to Q.

ANSWERS

a $d = |\vec{d}_2 - \vec{d}_1|$

$\Rightarrow d = |^{+}2\,\text{m} - 0\,\text{m}|$

$\Rightarrow d = 2\,\text{m}$

b $d = |\vec{d}_2 - \vec{d}_1|$

$\Rightarrow d = |^{+}5\,\text{m} - 0\,\text{m}|$

$\Rightarrow d = 5\,\text{m}$

c $d = |d_2 - d_1|$

$\Rightarrow d = |^{+}5\,\text{m} - {}^{+}2\,\text{m}|$

$\Rightarrow d = 3\,\text{m}$

d $\vec{d} = \vec{d}_2 - \vec{d}_1$

$\Rightarrow \vec{d} = {}^{+}5\,\text{m} - {}^{+}2\,\text{m}$

$\Rightarrow \vec{d} = {}^{+}3\,\text{m}$

Note: This answer indicates that Q is 3 m to the right relative to P.

e $\vec{d} = \vec{d}_2 - \vec{d}_1$

$\Rightarrow \vec{d} = {}^{+}2\,\text{m} - {}^{+}5\,\text{m}$

$\Rightarrow \vec{d} = {}^{-}3\,\text{m}$

Note: This answer indicates that P is 3 m to the left relative to Q.

PRACTICAL ACTIVITY 12.2.1

Vectors and scalars

MATERIALS

- large open space such as a school oval
- access to a GPS or long tape measure or trundle wheel
- compass or equivalent app
- 13 flags or stakes
- mallet
- logbook or equivalent to record your actual procedure and results

PART 1

1. Identify a suitable origin and place a flag there.
   - Mark out a 55 m radius circle.
   - Place flags on the circumference every 45° (8 flags).
2. Walk directly north of the origin for 55 m.
   - Place a flag at this position.
   - Record the vector along which you have just walked.
3. Walk directly back to the origin.
   - Record the vector along which you have just walked.
   - When you return to the origin, record:
     - the distance you walked
     - your displacement.
4. Repeat steps 2 and 3, except now walk:
   - 55 m east of the origin and back
   - 55 m south of the origin and back
   - 55 m west of the origin and back.

»

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PART 2

1 Walk directly east of the origin for 33 m and place a flag.
   - Record the vector along which you have just walked.

2 Walk directly north from this position until you reach the circumference of the circle.
   - Record your estimate of:
     - the distance you travelled north.
     - the vector along which you have just walked.
     - the distance from the origin you walked.
     - your displacement.

3 Using only the directions N–S, E–W, undertake a walk of 20 m followed by a walk that ends on the circle.
   - Record your estimate of:
     - the distance you travelled to the circle.
     - the displacement from the origin.

RESULTS

Summarise your results in visual form, such as a one-page poster or interactive slide.

DISCUSSION

1 Provide a definition and example from this practical activity of a:
   a scalar
   b vector.

2 Define:
   a origin
   b distance
   c displacement.

3 Demonstrate the difference between distance and displacement by referring to your results from:
   a Part 1
   b Part 2.

4 For a position on the circle that is south-west of the origin, state the distance and the displacement.

5 Calculate the distance travelled and the final displacement from the origin for the following walks.
   a 40 m E followed by 25 m W
   b 55 m N followed by 110 m S
   c 40 m S followed by 60 m N
   d $^{-}25$ m E followed by 25 m W

6 Describe the two possible walks that start with a 33 m walk to the south and end up on the circle.

7 Would a walk of 20 m west followed by a walk of 45 m south end on the circle? Explain with reference to your data.

8 Explain how this practical activity has affected your understanding of directed numbers. In your answer, refer to data you collected.

9 For this practical activity, identify and describe three things you did well and three things you believe you could improve. Consider such things as preparation, recording your actual procedures, measurement strategies, time spent actually doing the measurements, recording results, summarising and completion of questions.

10 Identify three ideas that this practical activity has helped you to understand better.

SECTION REVIEW 12.2

REMEMBERING

1 Write the formula for:

- **a** displacement
- **b** distance.

UNDERSTANDING

2 Explain how magnitude is related to displacement.

APPLYING

3 Perform the following displacement calculations.

- **a** $^{-}6\,\text{km} + {}^{+}5\,\text{km}$
- **b** $^{+}4\,\text{m} + {}^{+}5\,\text{m}$
- **c** $^{-}8\,\text{cm} - {}^{+}2\,\text{cm}$
- **d** $^{+}5\,\text{m} - {}^{+}2\,\text{m}$
- **e** $^{-}10\,\text{km} - {}^{-}3\,\text{km}$
- **f** $^{+}2\,\text{mm} - {}^{-}3\,\text{mm}$

ANALYSING

4 Explain this statement: 'Distance is related to the *magnitudes* of the individual changes of position'.

EVALUATING

5 Consider whether the mathematical formula for distance or your own way of thinking is better for working out distances.

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CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 Define 'scalar' and 'vector' and provide four examples for each.

2 Write the equation and define each term for:

- a displacement interval
- b distance interval.

3 Show the ways in which a vector can be represented.

CATEGORY QUESTIONS

4 Compare:

- a scalar and vector quantities
- b distance and displacement.

ELABORATION QUESTIONS

5 Explain why all displacements are differences.

6 A person throws a ball to a position that is 45 m directly west of them. It is picked up and thrown a further 45 m in a northerly direction. Explain why the distance associated with the displacement is less than the distance travelled by the ball.

EVIDENCE QUESTIONS

7 Create a realistic scenario involving at least three changes of position, for which the distance and displacement are different. Show how the scenario unfolds by representing the situation with:

- a a realistic drawing
- b vectors.

END-OF-CHAPTER EXAM

End-of-chapter test

1 Which of the following lists contains two scalar quantities and two vector quantities?

A Mass, displacement, distance, force

B Mass, displacement, time, length

C Mass, distance, time, energy

D Length, mass, velocity, time

2 A ball is thrown 40 m east, picked up and thrown a further 40 m south. The displacement of the ball is nearest to:

A 56 m.

B 80 m.

C 56 m, S45°E.

D 80 m, E45°S.

3 A particle moves along a number line. Starting at $^{+}15$ cm it moves to $^{+}20$ cm, then $^{-}30$ cm before stopping at the origin. The distance moved and the displacement relative to the starting position are, respectively:

A 85 cm; $^{-}20$ cm.

B 20 cm; $^{-}20$ cm.

C $^{+}85$ cm; 0 cm.

D 20 cm, 0 cm.

4 A vector is represented by an arrow whose length represents the ____________.

5 A bearing is an angle measured clockwise from ____________.

6 What is the difference between a scalar quantity and a vector quantity?

7 Contrast quadrant bearing and true bearing.

8 A particle moves from $d_1 = {}^{+}5$ cm to $d_2 = {}^{-}16$ cm. Calculate the distance, s. Show your working.

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13 LINEAR MOTION

Introduction

The study of motion can be divided into two categories: kinematics and dynamics. Kinematics is the description of motion. Dynamics is the study of the causes and effects of motion. Kinematics is principally associated with the change of position of objects relative to other positions as time passes, including distance, displacement, speed, velocity and acceleration. Dynamics is concerned with causes of motion, including concepts of force, energy and momentum.

In this chapter we look at kinematics, in particular the simplest form of motion – a single point particle moving along a straight line. We use graphs and equations as equivalent and complementary representations of the motion of these model particles.

Stimulus question

In the story of the hare and the tortoise, how is it that the slow-moving tortoise beat the faster hare?

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13.1 Displacement, velocity and acceleration

frame of reference
system within which measurements are made; point of view

The motion of objects can be described quantitatively by measuring their positions at particular times. Position is measured by reference to a suitable **frame of reference**. For example, the motion of a car or aeroplane can be described by assuming that Earth is stationary. A suitable origin is selected from which to measure changes in position on Earth as time changes. Change in position can then be analysed using scalar or vector quantities. Distance is a scalar because it is measured using a single scale. Displacement is a vector quantity because it uses two scales: distance and direction. In straight-line motion, the vectors can be represented as movement in the positive and negative directions on a number line.

centre of mass
the point in an extended particle where all the mass can be considered to be concentrated.

In order to simplify this analysis, it is assumed that all objects are point masses. A car, a runner or an aeroplane are all modelled as though their entire mass is concentrated at their **centre of mass**. More detailed analysis is required to determine what happens when extended objects interact, such as deformations in car crashes.

SYLLABUS LINK
Chapter 12 discusses scalar and vector quantities.

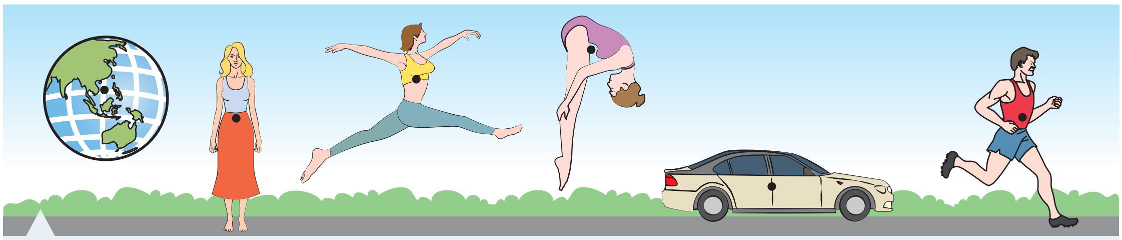

FIGURE 13.1.1 The centres of mass of some extended bodies (shown) are the points at which all the mass can be considered to be concentrated.

Movement along a straight line

interval
change in a quantity, such as time interval, displacement interval, velocity interval

velocity
time rate of change of displacement; speed with direction (vector)

speed
time rate of change of distance; magnitude of velocity (scalar)

acceleration
time rate of change of velocity (vector); magnitude of time rate of change of velocity (scalar); time rate of change of speed (scalar)

Measurements of position and time are fundamental to the description of motion. If a point mass is at the same position as time passes, it is stationary. If its position changes as time changes, it must have a speed, hence, velocity. If its speed and/or velocity changes as time changes, it is accelerating.

An **interval** is any change in a quantity. A time interval is a scalar difference between two times. Differences in position are vector displacement intervals. The magnitude of a displacement interval is a scalar distance interval.

Velocity is the rate at which the displacement changes during a time interval. Because the displacement change is a vector, velocity is a vector: **speed** is its magnitude. Similarly, acceleration is a vector because the change in velocity – the velocity interval – also occurs over a time interval. The term '**acceleration**' is used both to refer to the vector acceleration and the scalar magnitude of the vector. Just like speed and velocity, acceleration is ultimately determined using measurements of position and time.

Displacement interval

An object's position is the difference between the origin and its position relative to the origin.

In Figure 13.1.2, position A has a displacement interval of $^{+}25$ cm relative to O because:

$$\vec{s} = \vec{d}_2 - \vec{d}_1$$

$$\Rightarrow \vec{s} = {}^{+}25\text{ cm} - 0\text{ cm}$$

$$\Rightarrow \vec{s} = {}^{+}25\text{ cm}$$

Similarly, position B has a displacement interval of $^{-}40$ cm relative to O. (See Chapter 12 for a detailed discussion of displacement and distance equations.)

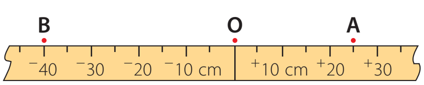

FIGURE 13.1.2 By defining a starting point or origin, opposite directions can be designated positive and negative values.

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WORKED EXAMPLE 13.1.1

In Figure 13.1.2, an object moves from O to A, then from A to B.

a Calculate the displacement interval of B relative to A.

b Calculate the distance interval between A and B.

c What is the total distance moved by the object?

ANSWERS

a $\vec{s} = \vec{d}_2 - \vec{d}_1$

$\Rightarrow \vec{s} = {}^-40\text{ cm} - {}^+25\text{ cm}$

$\Rightarrow \vec{s} = {}^-65\text{ cm}$

b $s = |\vec{s}| = 65\text{ cm}$

c Total distance is the sum of all the magnitudes of the displacement intervals:

$s = |{}^+25\text{ cm} - 0\text{ cm}| + |{}^-40\text{ cm} - {}^+25\text{ cm}|$

$s = 25\text{ cm} + 65\text{ cm}$

$s = 90\text{ cm}$

Time interval

Each moment of time is measured by a clock. A particular instant of time is called **instantaneous time**, t_{inst}. A **time interval**, t, is the difference between two instantaneous time measurements, t_1 and t_2:

$$t = t_2 - t_1$$

The time of day, such as 9:00 am, is really 9:00 hours after the zero of time (midnight, 0:00 am) for the day, where $t_1 = 0$.

13.1.1 What is displacement?

instantaneous time a particular moment on a clock

time interval time between two measurements of time

Unit of time

The SI unit for time, hence time interval, is the second, s.

SECTION REVIEW 13.1

REMEMBERING

1 Define:

a distance

b displacement

c interval

d centre of mass.

UNDERSTANDING

2 Explain why any measurement of time is a measure of a time interval.

3 Explain why any measurement of displacement is a measure of a displacement interval.

APPLYING

4 Calculate the time interval between:

a 3.0 s and 7.0 s

b 0.0245 s and 1.37×10^{-2} s.

5 Calculate the distance interval between:

a ${}^+15.1$ m and ${}^-4.3$ m

b ${}^-0.784$ m and ${}^+9.0$ mm.

13.2 Speed and velocity

13.2.1 Speed, velocity and displacement

In physics, speed relates to the distance covered (distance interval) in a time interval; velocity specifically relates to the change in displacement (displacement interval) during a time interval.

Average speed

average speed the one (constant) speed that would allow a particle to cover the total of the various distances of a journey in a given time interval

Speed, v, is a measure of how fast something is travelling. It is the rate at which distance changes as time changes. Speed is a scalar quantity because it measures only the magnitude of the rate of change of distance, s, a scalar, as the scalar time, t, changes.

Average speed is the one (constant) speed that would allow a particle to cover the total of the various distances of a journey in the time interval.

KEY FORMULA

$$v_{av} = \frac{s}{t} = \frac{|\vec{d}_2 - \vec{d}_1|}{t_2 - t_1}$$

Where:

v_{av} = average speed

s = distance interval

$t = t_2 - t_1$ = time interval

$|\vec{d}_2 - \vec{d}_1|$ = magnitude of the displacement interval

$$v_{av} = \frac{s}{t} = \frac{|\vec{d}_2 - \vec{d}_1|}{t_2 - t_1}$$

Note that the quantities s and t are intervals, not instantaneous values.

A flight from Coolangatta to Cairns, a distance of about 1500 km, might take 2.5 hours flying time. The average speed would be 600 km h^{-1}; however, the instantaneous speeds that occur during ascent, descent and other parts of the journey may vary considerably from the average speed.

Average velocity

KEY FORMULA

$$\vec{v}_{av} = \frac{\vec{s}}{t} = \frac{\vec{d}_2 - \vec{d}_1}{t_2 - t_1}$$

Where:

$\vec{v}_{av}$ = average velocity

$\vec{s} = \vec{d}_2 - \vec{d}_1$ = displacement interval

$t = t_2 - t_1$ = time interval

Velocity, $\vec{v}$, is a measure of how fast something is travelling in a particular direction. It is the rate at which displacement changes as time changes. Velocity is a vector quantity because it measures the rate of change of displacement, $\vec{s}$, a vector, as time, t, changes.

Average velocity, $\vec{v}_{av}$, is a vector because it is the average rate of change of displacement, a vector, as time changes.

$$\vec{v}_{av} = \frac{\vec{s}}{t} = \frac{\vec{d}_2 - \vec{d}_1}{t_2 - t_1}$$

Note that the quantities, $\vec{s}$ and t are intervals, not instantaneous values. Note also that, because the displacement has been multiplied by the scalar value, $1/t$, the vector displacement interval, $\vec{s} = \vec{d}_2 - \vec{d}_1$, and the average velocity vector, $\vec{v}_{av}$, are in the same direction.

Unit of speed and velocity

KEY FORMULA

$$[v] = \frac{[s]}{[t]} = \frac{\text{metre}}{\text{second}} = \text{m/s, m s}^{-1}$$

Where:

$[v]$ = unit of speed or velocity

$[s]$ = unit of distance or displacement

$[t]$ = unit of time

m = metre

s = second

The SI unit for speed and velocity is derived from their definitions. Both are defined in terms of the ratio of a distance measure to a time measure:

$$[v] = \frac{[s]}{[t]} = \frac{\text{metre}}{\text{second}} = \text{m/s, m s}^{-1}$$

Note: The square brackets mean 'unit of'; thus $[s]$ means 'unit of distance scale', $[t]$ means 'unit of time scale'.

WORKED EXAMPLE 13.2.1

A particle starts at the origin, moves 40 cm to the right before coming to rest 25 cm to the left of the origin 15 s later.

a Find the average speed.

b Calculate the average velocity.

ANSWERS

a Average speed is distance covered in a time interval. In this example, there are two separate displacements:

i from origin to $^{+}40$ cm

ii from $^{+}40$ cm to $^{-}25$ cm

$$v_{av} = \frac{s}{t} = \frac{\left|\vec{d}_2 - \vec{d}_1\right|_{i} + \left|\vec{d}_2 - \vec{d}_1\right|_{ii}}{t_2 - t_1}$$

$$\Rightarrow v_{av} = \frac{\left|40\text{ cm} - 0\text{ cm}\right| + \left|^{-}25\text{ cm} - {}^{+}40\text{ cm}\right|}{15\text{ s}}$$

$$\Rightarrow v_{av} = \frac{105\text{ cm}}{15\text{ s}}$$

$$\Rightarrow v_{av} = 7.0\text{ m s}^{-1}$$

b Average velocity is the displacement change in a time interval:

$$\vec{v}_{av} = \frac{\vec{s}}{t} = \frac{\vec{d}_2 - \vec{d}_1}{t_2 - t_1}$$

$$\Rightarrow \vec{v}_{av} = \frac{^{-}25\text{ cm} - 0\text{ cm}}{15\text{ s}}$$

$$\Rightarrow v_{av} = \frac{^{-}25\text{ cm}}{15\text{ s}}$$

$$\Rightarrow v_{av} = {}^{-}1.7\text{ m s}^{-1}$$

Instantaneous speed and instantaneous velocity

Speeds and velocities occur at particular moments, or instants, in time. But all measurements of speed and velocity depend on measurements of intervals of distance or displacement and intervals of time. If the time interval is very small, there is not much time for the speed or velocity to change markedly. For small time intervals, the difference between the average value and the instantaneous value is **negligible**. This means that the difference can be ignored for most purposes.

negligible so small it can be ignored; very little

SECTION REVIEW 13.2

REMEMBERING

1 Define the following terms.

a Instantaneous speed **b** Average speed **c** Negligible

2 Show how the SI unit can be deduced from the formula for speed.

UNDERSTANDING

3 What condition must be met so that average velocity and instantaneous velocity are regarded as the same value?

APPLYING

4 For a particle that takes 3.0 s to move along a line from $^{-}60.0$ cm to $^{-}90$ cm, calculate:

- **a** average speed
- **b** average velocity.

ANALYSING

5 An aircraft undertakes a return trip between Coolangatta and Cairns, a round trip of 3000 km. Its average velocity was zero. Use this example to explain why it is useful to distinguish between speed and velocity.

REFLECTING

6 Explain how the idea of a negligible time interval helps you to understand instantaneous speed.

13.3 Interpreting graphs: straight-line motion

One way to represent, or model, the motion of particles is by drawing graphs. The fundamental graph of motion is drawn from the basic measurements of position and time. Other graphs are derived from displacement and time data. Velocity–time graphs and acceleration–time graphs are derived from this basic data.

INQUIRING FURTHER

Investigate the top speeds and accelerations of a variety of animals and machines. Consider the following possibilities: fastest animals, such as humans, cheetahs and peregrine falcons; acceleration times of high-performance vehicles; fastest speeds reached on land and sea; accelerations of jet-propelled and rocket-propelled vehicles.

Displacement–time graphs

The position of a particle moving along a straight path can be recorded and plotted on a graph. The displacement from the origin is measured at various times. The position is designated by positive and negative numbers depending on which side of the origin the particle is observed. Displacement–time graphs show positive and negative distances from the origin.

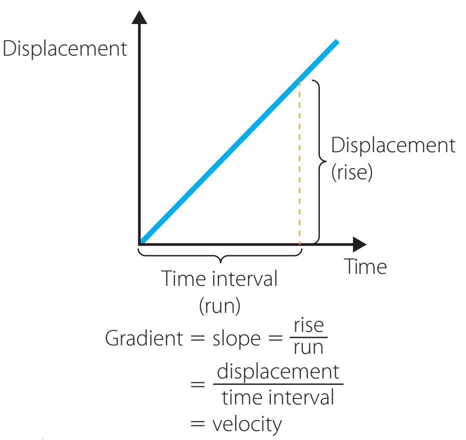

FIGURE 13.3.1 The gradient of this graph of displacement vs time is the constant velocity of an object.

Straight-line motion: constant speed and velocity

Figure 13.3.1 shows a displacement–time graph for an object moving along a straight line. The gradient of the graph is constant. This means that, in any time interval t, the displacement interval, $\vec{s}$, is steadily increasing. The velocity is therefore the same constant at every point; thus, the gradient can be used to deduce the velocity. We can say this because we note that:

- the rise up the distance axis is the displacement interval $\vec{s}$
- the run along the time axis is the corresponding time interval t.

Thus, the gradient (rise/run) is the velocity:

$$v = \frac{s}{t} = \text{gradient of } v\text{–}t \text{ graph}$$

If the displacement interval was negative (hence leading to a negative gradient), the velocity would be in the opposite direction to the positive velocity shown in Figure 13.3.1. The particle would be travelling towards the negative end of the number line.

The speed for straight-line motion is the magnitude of the gradient of the displacement–time graph. For Figure 13.3.1, the distance is the magnitude of the displacement and the slope is the positive velocity.

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For constant velocity, the gradient of the displacement–time graph is the same at all (instantaneous) points. The gradient at any one point is the same as the gradient calculated between any two points. Thus, the average velocity over the whole, or even any part of the journey, is the same as the instantaneous velocity at any one point in the journey.

KEY FORMULA

$v = \frac{s}{t}$ = gradient of v–t graph

Where:

v = speed

s = distance change (rise of v–t graph)

t = time interval (run of v–t graph)

Straight-line motion: non-constant speed and velocity

If the speed varies, the gradient of the displacement–time graph changes too. Figure 13.3.2 shows a non-constant change of distance from the origin with change of time. Speed is varying. At point P, the average speed between two points either side of the point marked becomes closer and closer to the gradient of the tangent at the point. Thus, the gradient of the tangent at the point is the instantaneous speed at that point. Again, we note that the instantaneous speed and instantaneous velocity differ only in respect of the positive or negative sign of the gradient.

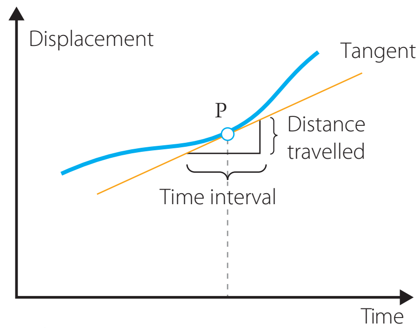

FIGURE 13.3.2 Instantaneous speed, v_{inst}, is the value of the gradient of the tangent to the distance–time graph.

Straight-line motion: constant speed–time graphs

Movement of a particle at constant speed is shown in Figure 13.3.3. From the definition of speed, we can deduce an algebraically equivalent equation:

$$v = \frac{s}{t}$$
$$\Rightarrow s = vt$$

This algebraic equation, applied to the graph, reveals that the area under the speed–time graph between any two times (the time interval, t) can be used to deduce the distance travelled (distance interval, s) (Figure 13.3.3).

When an object changes from one constant speed, v_1, to another constant speed, v_2, in a very short amount of time, the change in speed is often regarded as being instantaneous. Truly instantaneous speed change is impossible for the same reasons that truly instantaneous distance change is impossible. If a particle travelling at a constant speed v_1 for a time interval t_1 changes (in a negligible time interval) to new speed v_2 for a time interval t_2 and so on, the distance travelled will be the sum of the individual distances:

$$s = v_1t_1 + v_2t_2 + \cdots$$

KEY FORMULA

$v = \frac{s}{t}$

$\Rightarrow s = vt$

Where:

v = speed

s = distance travelled

t = time elapsed

KEY FORMULA

$s = v_1t_1 + v_2t_2 + \cdots$

Where:

s = total distance travelled

v_1t_1 = distance travelled at constant speed v_1 in first time interval t_1

v_2t_2 = distance travelled at constant speed v_2 in second time interval t_2

'...' means this goes on for as many constant speeds in time intervals as there are in the motion described by the graph

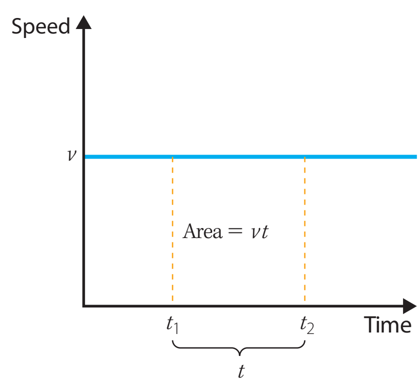

FIGURE 13.3.3 The area under this graph of speed vs time is the distance travelled by an object.

WORKED EXAMPLE 13.3.1

An athlete runs at $20\,\text{km}\,\text{h}^{-1}$ for 15 minutes. She then gets a stitch and slows to $15\,\text{km}\,\text{h}^{-1}$ for the next hour. The speed–time graph is shown in Figure 13.3.4.
Calculate how far, in kilometres, the runner travels:

a in the first 15 minutes.

b in total.

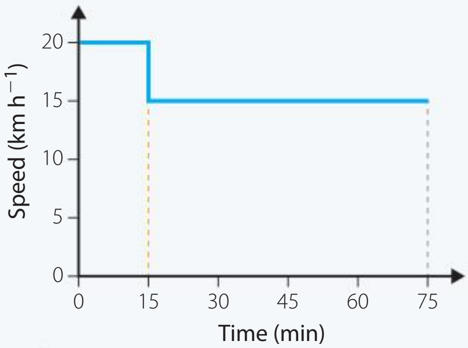

FIGURE 13.3.4

ANSWERS

a Distance equals the area under the speed–time graph:
$s = \text{area} = (20\,\text{km}\,\text{h}^{-1} \times 0.25\,\text{h})$
$\Rightarrow s = 5.0\,\text{km}$

b $s = \text{areas} = s_1 + s_2$
$\Rightarrow s = (20\,\text{km}\,\text{h}^{-1} \times 0.25\,\text{h}) + (15\,\text{km}\,\text{h}^{-1} \times 1.0\,\text{h})$
$\Rightarrow s = 5.0\,\text{km} + 15\,\text{km}$
$\Rightarrow s = 20\,\text{km}$

SECTION REVIEW 13.3

REMEMBERING

1 Define the following terms.
  a Velocity interval
  b Average velocity
  c Instantaneous velocity
  d Acceleration

2 Identify the basic measurements from which all motion is described.

3 Identify the graph whose gradient can be used to find:
  a velocity
  b acceleration.

4 Identify the graph whose area can be used to find:
  a the displacement interval
  b the velocity interval.

UNDERSTANDING

5 Explain this statement: 'Other graphs are derived from displacement and time data'.

APPLYING

6 A particle moves at a constant speed of $10\,\text{m}\,\text{s}^{-1}$ for 5.0 s. Sketch the following graphs.
  a Speed–time
  b Displacement–time

7 Calculate the change of speed of a particle moving at a constant acceleration of $6.0\,\text{m}\,\text{s}^{-2}$ for 3.0 s.

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ANALYSING

8 The graph in Figure 13.3.5 shows the motion of a car.

a Calculate how far, in kilometres, the car travels:

i in the first 30 minutes

ii in total.

b Calculate the average speed for the journey.

REFLECTING

9 'Graphs are models.' Explain with reference to displacement–time and velocity–time graphs. Include in your answer how the models can be used to derive other quantities.

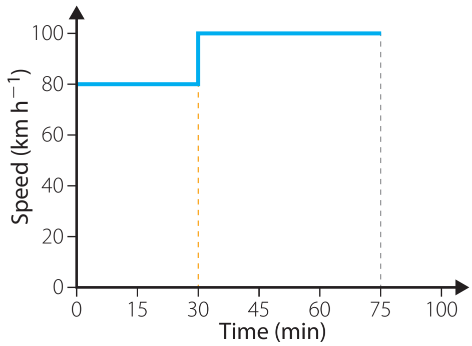

FIGURE 13.3.5 Speed–time graph

13.4 Straight-line motion: uniformly accelerated motion

Particles may travel along a straight-line path at increasing or decreasing speeds. When the speed or velocity of a particle changes, acceleration occurs. The acceleration may be uniform or non-uniform. Non-uniformly accelerated motion is quite complicated to analyse compared to uniformly accelerated motion. We shall therefore only consider uniform (constant) acceleration along a straight line.

Acceleration

Acceleration is the rate of change of velocity. Velocity change, $\vec{v}$, always occurs over a time interval, t. Thus,

$$\vec{a} = \frac{\vec{v}}{t}$$

Note that $\vec{v}$ and t are intervals of velocity change and time change respectively.

KEY FORMULA

$$\vec{a} = \frac{\vec{v}}{t}$$

Where:

$\vec{a}$ = acceleration

$\vec{v}$ = velocity change

t = time interval

Unit of acceleration

The SI unit for acceleration is derived from the definition of speed or velocity change and time interval:

$$[a] = \frac{[v]}{[t]} = \frac{\text{m s}^{-1}}{\text{s}} = \text{m s}^{-2}$$

The unit can be read as 'metres per second of speed change in each second: (metres per second) per second'.

KEY FORMULA

$$[a] = \frac{[v]}{[t]} = \frac{\text{m s}^{-1}}{\text{s}} = \text{m s}^{-2}$$

Where:

$[a]$ = unit of acceleration

$[v]$ = unit of speed or acceleration

$[t]$ = unit of time

m = metre

s = second

Uniform acceleration along a straight line: graphs

Graphs are a very powerful way to represent straight-line motion. We shall look at two graphical ways to represent uniform acceleration along a straight line: velocity–time and acceleration–time graphs.

Velocity–time graphs

Uniform acceleration means that the rate of change of velocity is constant. This means that the velocity–time graph has a constant gradient (Figure 13.4.1).

In any time interval t, the velocity interval, $\vec{v}$, is steadily increasing – there is a uniform change in velocity. Thus, the gradient can be used to deduce the acceleration. This can be said because:

- the rise up the velocity axis is the velocity interval or velocity change, $\vec{v}$
- the run along the time axis is the corresponding time interval, t.

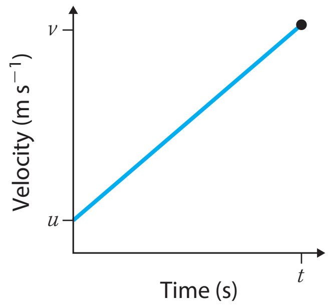

FIGURE 13.4.1 For constant acceleration, the velocity–time graph has a constant gradient.

Thus, the gradient (rise/run) is the acceleration:

$$\vec{a} = \frac{\vec{v}}{t}$$

KEY FORMULA

$$\vec{a} = \frac{\vec{v}}{t}$$

$$\vec{a} = \frac{\vec{v}_2 - \vec{v}_1}{t_2 - t_1}$$

Where:

$\vec{a}$ = acceleration

$\vec{v} = \vec{v}_2 - \vec{v}_1$ = velocity change

$t = t_2 - t_1$ = time interval

Note that the quantities $\vec{v}$ and t are intervals, not instantaneous values. The equation can be written:

$$\vec{a} = \frac{\vec{v}_2 - \vec{v}_1}{t_2 - t_1}$$

Note also that, because the velocity interval $\vec{v} = \vec{v}_2 - \vec{v}_1$ has only been multiplied by the scalar value, $1/t$, the velocity interval and the acceleration vector, $\vec{a}$, are in the same direction.

If the velocity interval were negative (negative gradient), the acceleration would be in the opposite direction to the positive acceleration shown; that is, it would be negative acceleration (**deceleration**). Compared to movement towards the positive direction, negative acceleration may be a reduction in speed with no change in direction. It may also be an increase of speed in the negative direction.

deceleration
negative acceleration

Each instantaneous point on the velocity–time graph has the same gradient as the average gradient; thus, the average and instantaneous accelerations have the same value throughout the motion.

INQUIRING FURTHER

In Aesop's tortoise and hare fable, the slow but steady tortoise races against the faster hare. Let's analyse this. The hare rushes off for a good portion of the distance before stopping for a long rest (consider the rest to take at least one hour). The tortoise plods on and arrives at the finishing line well ahead of the hare.

Find information about the realistic speeds of a hare and a tortoise.

From this information, decide on a realistic distance and time over which the race is conducted.

Compare the motion of the tortoise and the hare by sketching graphs of:

a distance–time.

b velocity–time.

c acceleration–time.

On the graphs, show the realistic values used.

Discuss any assumptions you made.

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Acceleration–time graphs

The acceleration–time graph for uniformly accelerated motion looks like Figure 13.4.2.

From the definition of acceleration, we can deduce an algebraically equivalent equation:

KEY FORMULA

$$a = \frac{v}{t}$$

$$\Rightarrow v = at$$

Where:

v = speed interval

t = time interval

a = constant acceleration

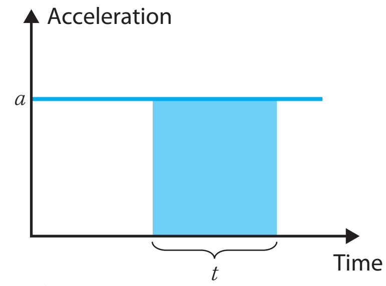

FIGURE 13.4.2 The area under this graph of acceleration vs time is the change in speed of an object.

This algebraic equation, applied to the graph, reveals that the area under the acceleration–time graph can be used to deduce the speed change (Figure 13.4.2).

SECTION REVIEW 13.4

REMEMBERING

1 **a** Define each symbol in the equation:

$$\vec{a} = \frac{\vec{v}}{t}$$

b State the direction of the acceleration vector.

2 Write the unit for acceleration in words to show how it relates to velocity change.

3 State what is represented by the area under an acceleration–time graph.

UNDERSTANDING

4 Explain how a velocity–time graph can be used to derive acceleration.

5 Explain what is meant by negative acceleration (deceleration).

APPLYING

6 A particle that is travelling along a straight line at 5.0 m s^{-1} accelerates for 4.0 s at a rate of 3.0 m s^{-2}.

a Sketch the acceleration–time graph.

b Find the final speed of the particle.

c Find the speed increase between 2.0 s and 3.0 s.

ANALYSING

7 Explain how a train can have a negative acceleration yet still be travelling in the positive direction.

REFLECTING

8 Both the definition of velocity and the definition of acceleration involve the idea of interval. Describe how you use this when analysing graphs.

13.5 Interpreting graphs

When interpreting graphs, the following should be considered:

- Type of graph: displacement–time; velocity–time; acceleration–time
- Axis scale: vertical (displacement, velocity, acceleration); horizontal (time)
- Gradient: displacement–time (velocity); velocity–time (acceleration)
- Area under graph: velocity–time (change of displacement – displacement interval); acceleration–time (change in velocity – velocity interval)

WORKED EXAMPLE 13.5.1

A snail starts at a position 20 cm from the origin and then moves to a new position 40 cm further away before going back past the origin to a position 20 cm on the other side of the origin. It finally ends up at the origin. The positions are shown in Figure 13.5.1.

The displacement–time graph of the motion is shown in Figure 13.5.2.

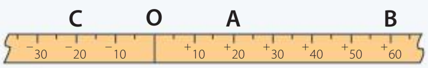

FIGURE 13.5.1 A snail moves along a straight line from $^{+}20$ cm to $^{+}60$ cm then to $^{-}20$ cm and ends up at the origin, O.

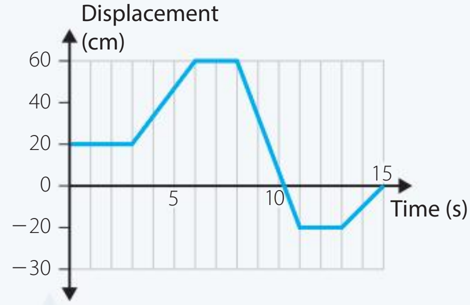

FIGURE 13.5.2 Cartesian graph of the motion of a snail along a straight line

1. Calculate the distance travelled by the snail.
2. Find the final displacement of the snail relative to:
   a. the starting point.
   b. the origin.
3. a. Calculate the average velocity between 3 s and 6 s.
   b. Calculate the velocity at:
      i. 4 s.
      ii. 10 s.

ANSWERS

This question involves analysing a displacement–time graph. Key ideas are displacement–time graph, axis values and gradient.

1. By reading from the axis:
   s = sum of individual distances

   $s = \left|{}^{+}60\text{ cm} - {}^{+}20\text{ cm}\right| + \left|{}^{+}60\text{ cm} - {}^{-}20\text{ cm}\right| + \left|0\text{ cm} - {}^{-}20\text{ cm}\right|$

   $\Rightarrow s = 40\text{ cm} + 80\text{ cm} + 20\text{ cm}$

   $\Rightarrow s = 140\text{ cm}$

2. a. $\vec{s} = 0\text{ cm} - {}^{+}20\text{ cm}$

   $\Rightarrow \vec{s} = {}^{-}20\text{ cm}$

   i.e. the snail is 20 cm to the left of the starting point.

   b. The graph shows the snail at the origin after the movement:

   $\Rightarrow$ relative to origin, $s = 0$ cm

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3 **a** By calculating the gradient:

$$\vec{v}_{av} = \frac{\vec{d}_2 - \vec{d}_1}{t_2 - t_1}$$

$$\Rightarrow \vec{v}_{av} = \frac{{}^{+}60\text{ cm} - {}^{+}20\text{ cm}}{6\text{ s} - 3\text{ s}}$$

$$\Rightarrow \vec{v}_{av} = \frac{{}^{+}40\text{ cm}}{3\text{ s}}$$

$$\Rightarrow \vec{v}_{av} = {}^{+}13.3\text{ cm s}^{-1}$$

b **i** $\vec{v}_{av}(3\text{ s to }6\text{ s}) = v_{inst}(4\text{ s})$

$$\Rightarrow v_{inst}(4\text{ s}) = {}^{+}13.3\text{ cm s}^{-1}$$

ii $\vec{v}_{av}(8\text{ s to }11\text{ s}) = v_{inst}(10\text{ s})$

$$\Rightarrow v_{inst}(10\text{ s}) = \frac{{}^{-}20\text{ cm} - {}^{+}60\text{ cm}}{3\text{ s}}$$

$$\Rightarrow v_{inst} = \frac{{}^{-}80\text{ cm}}{3\text{ s}}$$

$$\Rightarrow v_{inst} = {}^{-}27\text{ cm s}^{-1}\ ({}^{-}26.7\text{ cm s}^{-1})$$

WORKED EXAMPLE 13.5.2

Use the velocity–time graph for an object shown in Figure 13.5.3 to answer the following questions.

a Find the speed at these times:

i 20 s **ii** 32 s

b Calculate the acceleration:

i between 0 s and 10 s. **ii** at 32 s.

c Find the distance travelled:

i in the first 10.0 s. **ii** between 10.0 s and 30.0 s.

iii between 30.0 s and 34.0 s. **iv** in the first 15 s.

d Find the time taken for the object to travel 70 m.

e Find the average speed of the object for the trip.

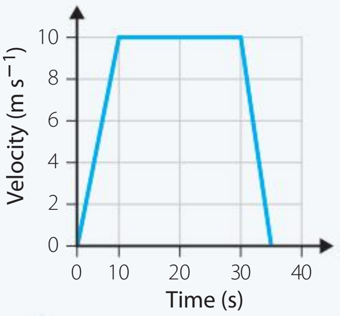

FIGURE 13.5.3 Velocity–time graph for an object moving along a straight line

ANSWERS

This question is about analysing a velocity–time graph. The key ideas are velocity–time graph, axis values, gradient and area.

a By reading from the axis:

i 10 m s^{-1} **ii** 2 m s^{-1}

b By calculating the gradient:

i $\vec{a}_{av}(0\text{ s to }10\text{ s}) = \frac{{}^{+}10\text{ m s}^{-1} - 0\text{ m s}^{-1}}{10\text{ s} - 0\text{ s}}$

$$\Rightarrow a_{inst} = \frac{{}^{+}10\text{ m s}^{-1}}{10\text{ s}}$$

$$\Rightarrow a_{inst} = {}^{+}1.0\text{ m s}^{-2}$$

Note that the acceleration at any instantaneous time between 0 s and 10 s is the same value ($^{+}1.0\ \text{m s}^{-2}$).

ii $\vec{a}_{av}(30\ \text{s to }34\ \text{s}) = a_{inst}(32\ \text{s})$

$$\Rightarrow a_{inst}(32\ \text{s}) = \frac{0\ \text{m s}^{-1} - {}^{+}10\ \text{m s}^{-1}}{34\ \text{s} - 30\ \text{s}}$$

$$\Rightarrow a_{inst} = \frac{{}^{-}10\ \text{m s}^{-1}}{4\ \text{s}}$$

$$\Rightarrow a_{inst} = {}^{-}2.5\ \text{m s}^{-2}$$

c By area:

i s = area under v–t graph

$$\Rightarrow s = \frac{1}{2}(10\ \text{m s}^{-1} \times 10\ \text{s})$$

$$\Rightarrow s = 50\ \text{m}$$

ii s = area under v–t graph

$$\Rightarrow s = 10\ \text{m s}^{-1} \times (30\ \text{s} - 10\ \text{s})$$

$$\Rightarrow s = 10\ \text{m s}^{-1} \times 20\ \text{s}$$

$$\Rightarrow s = 200\ \text{m}$$

iii s = area under v–t graph

$$\Rightarrow s = \frac{1}{2}(10\ \text{m s}^{-1} \times (34\ \text{s} - 30\ \text{s})$$

$$\Rightarrow s = \frac{1}{2}(10\ \text{m s}^{-1} \times 4\ \text{s})$$

$$\Rightarrow s = 20\ \text{m}$$

iv s = area under v–t graph

$$\Rightarrow s = 50\ \text{m} + 10\ \text{m s}^{-1} \times (15\ \text{s} - 10\ \text{s})$$

$$\Rightarrow s = 50\ \text{m} + 10\ \text{m s}^{-1} \times 5\ \text{s}$$

$$\Rightarrow s = 100\ \text{m}$$

d s = area under v–t graph

$$\Rightarrow s = 50\ \text{m} + 10\ \text{m s}^{-1} \times (t - 10)\ \text{s} = 70\ \text{m}$$

$$\Rightarrow 50\ \text{m} + 10\ \text{m s}^{-1} \times t - 10\ \text{m s}^{-1} \times 10\ \text{s} = 70\ \text{m}$$

$$\Rightarrow 10\ \text{m s}^{-1} \times t = 70\ \text{m} - 50\ \text{m} + 100\ \text{m}$$

$$\Rightarrow t = \frac{120\ \text{m}}{10\ \text{m s}^{-1}}$$

$$\Rightarrow t = 12\ \text{s}$$

e $$\vec{v}_{av} = \frac{{}^{+}50\ \text{m} + 200\ \text{m} + 20\ \text{m}}{34\ \text{s} - 0\ \text{s}}$$

$$\Rightarrow \vec{v}_{av} = \frac{{}^{+}270\ \text{m}}{34\ \text{s}}$$

$$\Rightarrow \vec{v}_{av} = {}^{+}7.9\ \text{m s}^{-1}$$

Note: average speed is found by finding the total distance and dividing by time.

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WORKED EXAMPLE 13.5.3

A cruise ship accelerates at a constant rate for 10.0 minutes until it reaches a speed of 10 m s^{-1}. It then continues to travel in a straight line for 20.0 minutes at 10 m s^{-1}.

a Sketch a velocity (m s^{-1}) versus time (s) graph for the ship for the 30 minutes.

b Calculate the ship's acceleration for the first 10.0 minutes, in m s^{-2}.

c Sketch an acceleration versus time graph for the ship for the 30 minutes.

ANSWERS

This is a question about sketching a velocity–time graph. The key ideas are velocity–time graph, axis values, gradient and area.

a Convert minutes to seconds, so that the time axis goes from 0 to 1800 s.
Velocity axis goes from 0 m s^{-1} to 10 m s^{-1}.
Mark appropriate given and calculated values on the axes, as shown in Figure 13.5.4.

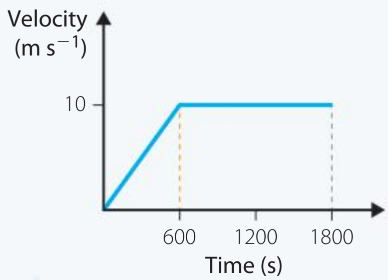


FIGURE 13.5.4

b $\vec{a}$ = gradient of $\vec{v}$–t graph

$$\vec{a} = \frac{\vec{v}_2 - \vec{v}_1}{t_2 - t_1}$$

$$\Rightarrow \vec{a} = \frac{10\ \text{m s}^{-1} - 0\ \text{m s}^{-1}}{600\ \text{s} - 0\ \text{s}}$$

$$\Rightarrow \vec{a} = \frac{10\ \text{m s}^{-1}}{600\ \text{s}}$$

$$\vec{a} = 1.7 \times 10^{-2}\ \text{m s}^{-2}\ (1.67 \times 10^{-2}\ \text{m s}^{-2})$$

c Mark appropriate given and calculated values on the axes, as shown in Figure 13.5.5.

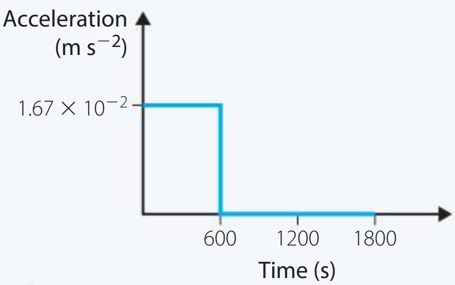


FIGURE 13.5.5

WORKED EXAMPLE 13.5.4

A car initially travelling at a speed of $4.0\,m\,s^{-1}$ accelerates at $2.0\,m\,s^{-2}$ for 12 s.

a Sketch the acceleration–time graph for the car.

b Find the velocity, v, of the car after 12.0 s.

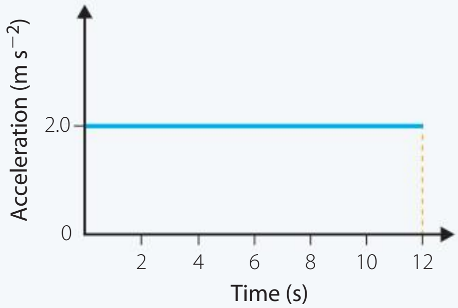
c Sketch the velocity–time graph.

d Find the distance moved by the car in 8.0 s.

ANSWERS

This is a question about analysing an acceleration–time graph. The key ideas are acceleration–time graph, axis values and area.

a Mark appropriate given values on the axes, as shown.



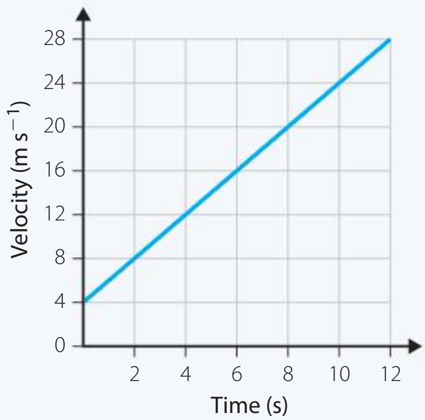
b Area under a–t graph = *change* in velocity

$\Rightarrow \vec{v} - 4\,m\,s^{-1} = 2\,m\,s^{-2} \times 12\,s$

$\Rightarrow \vec{v} - 4\,m\,s^{-1} = 24\,m\,s^{-1}$

$\Rightarrow \vec{v} = 28\,m\,s^{-1}$

c



d By axis and area

Read velocity value from graph:

$v_{8\,s} = 20\ m\ s^{-1}$

Area of a trapezium = average height × base

$$\text{area} = s = \frac{4\,m\,s^{-1} + 20\,m\,s^{-1}}{2} \times 8\,s$$

$\Rightarrow s = 12\,m\,s^{-1} \times 8\,s$

$\Rightarrow s = 96\,m$

SECTION REVIEW 13.5

REMEMBERING

1 List the four things that should be considered when solving problems involving graphs.

2 Copy and complete the following table.

TYPE OF GRAPH	GRADIENT REPRESENTS	AREA REPRESENTS

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UNDERSTANDING

3 Explain how the concept of interval relates to the gradient of kinematic graphs.

4 Explain how the concept of interval relates to the area of kinematic graphs.

APPLYING

5 Figure 13.5.6 shows a walk undertaken by Simi from school to home. She visits shops and a friend along the way.

a Find the displacement of school from Simi's home.

b Find Simi's velocity, in m s^{-1}:

i between school and the shops

ii 20 minutes after leaving school.

c Calculate the distance Simi walked.

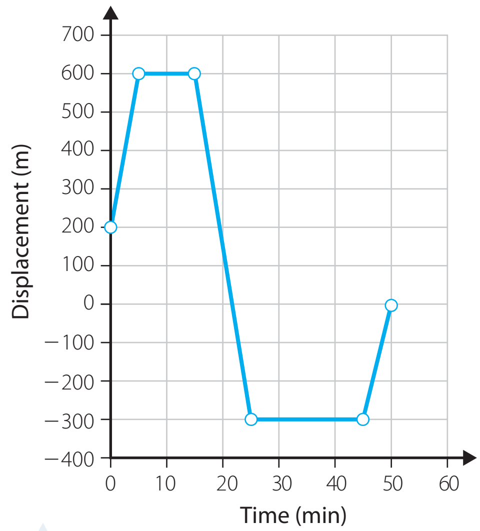

FIGURE 13.5.6

6 A train accelerates uniformly from rest to 8.0 m s^{-1} in 25 s. It then travels for 50 s at 8.0 m s^{-1} before slowing uniformly to a stop in 12 s (Figure 13.5.7).

a Find the distance travelled by the train in the first 20 s.

b Calculate the distance between the two stops.

c Find the acceleration of the train in:

i the first 10 s of the train's motion

ii the last 10 s of the train's motion.

d Sketch the acceleration versus time graph for the motion of the train.

e Calculate the time taken for the train to travel 300 m.

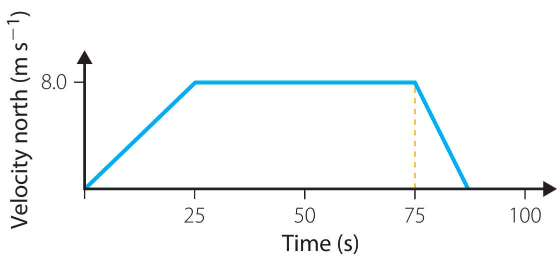

FIGURE 13.5.7

ANALYSING

7 A car travels at 70 km h^{-1} for 1.0 h and then at 80 km h^{-1} for 2.0 h. Explain why the average speed is not 75 km h^{-1}.

13.6 Solving problems using algebra

The motion of a particle that is accelerating uniformly along a straight-line path can be represented in numerous ways: described in words, captured through multi-flash photographs, recorded on video, measured in relation to position and time and drawn on graphs or by using algebraic equations. All of these representations are models that describe the same motion and are therefore equivalent representations.

Graphical representations and algebraic representations are the most common ways by which we analyse uniformly accelerated motion. Algebraic representations or equations and graphical representations say the same thing.

For example, consider an object – it might be a car or a bicycle – that has an initial velocity of u at the moment we start making measurements. It is accelerating at a constant rate a, as shown by the straight line on the graph (Figure 13.6.1). After a time interval, t, its final velocity is v, which is greater than its initial speed. Note that the time interval, t, is taken from $t_1 = 0$. During the time interval, the object covers a distance interval of s.

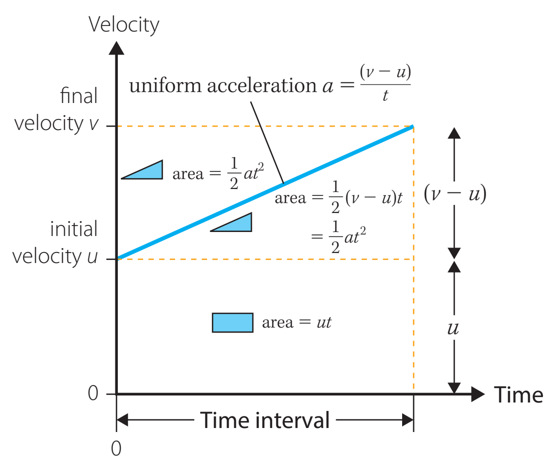

FIGURE 13.6.1 Generalised motion of an object accelerating uniformly with increasing speed along a straight line.

The equations are derived for constantly accelerated motion in a straight line where:

- initial speed = u
- final speed = v
- acceleration = a
- time interval = t (t is not an instantaneous time)
- distance interval = s (s is not a particular point on a line).

Note that the vector sign from the variables, u, v and a have been removed. The sign convention for positive motion and the oppositely directed negative motion variables are relied upon.

From the definition of acceleration, the gradient of the line can be determined:

$$a = \frac{v - u}{t}$$

$$\Rightarrow v - u = at$$

$$\Rightarrow v = u + at$$

This equation connects u, v, a and t.

Finding the area under the graph as the sum of the small rectangle and the triangle gives:

$$s = ut + \frac{1}{2}(v - u)t$$

$$s = ut + \frac{1}{2}(at)t$$

$$s = ut + \frac{1}{2}at^2$$

This equation connects s, u, a and t.

Alternatively, finding the area under the graph as the difference between the large rectangle and the triangle gives:

$$s = vt - \frac{1}{2}at^2$$

This equation connects s, v, a and t.

Another useful equation that can be derived from these two equations can be found using algebra on the first two equations:

$$v = u + at$$

Squaring both sides:

$$\Rightarrow v^2 = (u + at)^2$$

$$v^2 = u^2 + 2uat + a^2t^2$$

Keeping in mind that $s = ut + \frac{1}{2}at^2$, we can factorise this expression, to find another equation:

$$v^2 = u^2 + 2a\left(ut + \frac{1}{2}at^2\right)$$

$$\Rightarrow v^2 = u^2 + 2as$$

This equation connects s, u, v and a.

Using the same graph, finding the area under the graph as a trapezium gives:

$$s = \text{average height} \times t$$

$$s = \frac{1}{2}(u + v) \times t$$

This equation connects s, u, v and t.

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Summary of motion in a straight line at constant acceleration

The two main methods used for analysing motion in a straight line are graphical and algebraic. Graphical analysis is often a simpler, more visual way that will give the same answer to a problem as algebraic techniques. Graphical analysis should be attempted wherever possible.

Graphically

v = gradient of the s–t graph
s = area under the v–t graph
a = gradient of the v–t graph
Speed change, v = area under the a–t graph

Algebraically

The equations for straight-line motion with constant acceleration are:

$$v = u + at$$

$$s = ut + \frac{1}{2}at^2 \qquad s = vt - \frac{1}{2}at^2$$

$$s = \frac{u+v}{2}t$$

$$v^2 = u^2 + 2as$$

These are sometimes referred to as the *suvat* equations. Each of these equations involves four variables: s, u, v, a or t. When solving problems algebraically, you will need to know or deduce the values of three of the five variables s, u, v, a, t. The fourth can be found by simple substitution in the appropriate equation. It is then possible to use another equation to find the fifth variable. Note that s and t are intervals in these equations.

WORKED EXAMPLE 13.6.1

An aeroplane travelling at $40\ \text{m s}^{-1}$ accelerates to $100\ \text{m s}^{-1}$ in 40 s.

a Calculate the acceleration of the aeroplane.

b Determine how far the aeroplane travelled while accelerating.

ANSWERS

a $s = ?,\ u = 40\ \text{m s}^{-1},\ v = 100\ \text{m s}^{-1},\ a = ?,\ t = 4.0\ \text{s}$

$$v = u + at$$

$$a = \frac{v-u}{t}$$

$$\Rightarrow a = \frac{100\ \text{m s}^{-1} - 40\ \text{m s}^{-1}}{4.0\ \text{s}}$$

$$\Rightarrow a = \frac{60\ \text{m s}^{-1}}{4.0\ \text{s}}$$

$$\Rightarrow a = 15\ \text{m s}^{-2}$$

b $s = ?,\ u = 40\ \text{m s}^{-1},\ v = 100\ \text{m s}^{-1},\ a = 15\ \text{m s}^{-2},\ t = 4.0\ \text{s}$

$$s = ut + \frac{1}{2}at^2$$

$$\Rightarrow s = 40\ \text{m s}^{-1} \times 4.0\ \text{s} + \frac{1}{2} \times 15\ \text{m s}^{-2} \times (4.0\ \text{s})^2$$

$$\Rightarrow s = 160\ \text{m} + 120\ \text{m}$$

$$\Rightarrow s = 280\ \text{m}$$

Solving kinematic problems

Use these steps to solve most kinematic problems involving particles moving along a straight line with uniform acceleration:

- Assign values to s, u, v, a, t.
  (Remember that s and t are intervals, not instantaneous values.)
- Identify any missing values.
- Sketch a v–t graph.
- Write known values onto the graph.
- Assess whether it is possible to find the:
  - gradient (acceleration)
  - area (distance or displacement).
- Use the graph to solve for the missing values.
- Use *suvat* formulas if necessary.

Graphical analysis is often simpler and more obvious than algebraic analysis. Acceleration (gradient) and distance (area) can often be calculated easily once a v–t graph has been sketched and relevant data points identified.

Both methods yield the same answers because they are both models of the same motion.

SECTION REVIEW 13.6

REMEMBERING

1 Consider uniformly accelerated motion where the initial velocity is non-zero.

a Sketch the velocity–time graph that represents the motion. Indicate on the graph how to find acceleration and displacement.

b Write down the equations that represent the motion (***suvat*** equations). Define each of the variables.

UNDERSTANDING

2 Explain how the ***suvat*** equations can be used to find all five variables when you only have three variables.

3 Compare the use of graphical and algebraic methods of analysing motion, providing one similarity and one difference.

APPLYING

4 A cyclist accelerates from $5.0\,\text{m}\,\text{s}^{-1}$ to $8.0\,\text{m}\,\text{s}^{-1}$ in 15 s.

a Calculate the acceleration of the cyclist.

b Determine how far the cyclist travelled while accelerating.

5 A car travels 50.0 m from a standing start in 2.5 s. Calculate:

a the acceleration

b its final speed.

ANALYSING

6 A driver travelling at $10\,\text{m}\,\text{s}^{-1}$ sees a child run onto the road 10 m away. The driver takes 0.2 s to respond (reaction time). The maximum braking acceleration of the car is $^{-}8.0\,\text{m}\,\text{s}^{-2}$.

a Sketch the velocity–time graph.

b Find how far the car travels before the driver applies the brakes (reaction distance).

c Find the time taken to come to a stop (braking time).

d Find the distance travelled by the car while braking (braking distance).

e Find the total distance travelled before coming to a stop (stopping distance).

REFLECTING

7 Both the definition of velocity and the definition of acceleration involve the idea of interval. Describe how you will keep this in mind when using algebraic formulas to solve problems.

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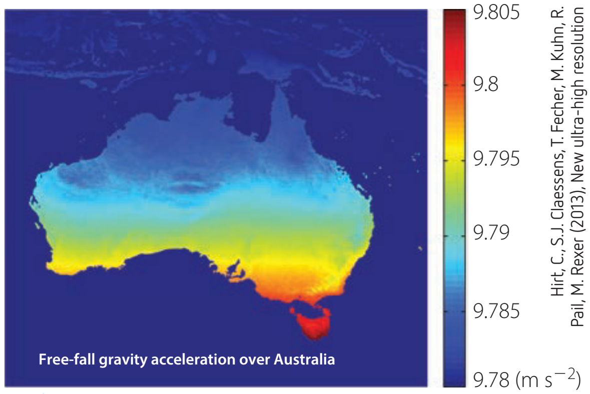
13.7 Acceleration due to gravity

An interesting example of constantly accelerated motion in a straight line is when an object falls or is thrown straight down, or is projected upwards vertically. The object accelerates uniformly because the acceleration of all masses near Earth' surface is constant. Consequently, these up or down motions can be treated as uniformly accelerated motions.

Projectile motion in a vertical straight line

Every mass produces a gravitational field around it. This gravitational field applies gravitational force on other masses. Gravitational force is, therefore, the force applied by the gravitational field of one mass on another mass. This force is usually referred to as gravity.

Earth has a large mass of 6.0×10^{24} kg. Its gravitational field is proportionately much larger than the gravitational field surrounding familiar objects. In the model world of point masses, air resistance and buoyancy forces can be regarded as negligible. Therefore, once an object is released or thrown, the only (non-negligible) force acting upon it is the gravitational force applied by Earth's gravitational field.



Hirt, C., S.J. Claessens, T. Fecher, M. Kuhn, R. Pail, M. Rexer (2013), New ultra-high resolution picture of Earth's gravity field, Geophysical Research Letters, Vol 40, doi: 10.1002/grl.50838.

FIGURE 13.7.1 Variations of the acceleration due to gravity across Australia.

Near Earth's surface, gravity will cause a force on an object, which results in that object accelerating vertically downwards with a constant acceleration. This is known as gravitational acceleration, and is given the symbol g. The value of g that gives sufficiently accurate answers for most purposes is:

$$g = 9.80\,\text{m s}^{-2}$$

The value of g varies slightly around the world. In Australia, g is greatest in southern Tasmania ($9.805\,\text{m s}^{-2}$). Across Queensland, its value varies by about 1% from Brisbane ($9.79\,\text{m s}^{-2}$) to Cairns ($9.78\,\text{m s}^{-2}$) (Figure 13.7.1).

13.7.1

SCIENCE AS A HUMAN ENDEAVOUR

An experiment to show that air affects the motion of a hammer and a feather was done by *Apollo 15* astronaut Commander David Scott. He dropped both on the Moon, which has no atmosphere. With no air friction, both objects fell at the same rate. That's quite different from the results on Earth, where the atmosphere applies different air resistance and buoyancy forces on a hammer and a feather. NASA has uploaded the video of the experiment to the internet. Use video analysis to estimate the acceleration due to gravity on the Moon. Video frame rates in 1971 were $29.97\,\text{s}^{-1}$.

Getty Images/NASA/SCIENCE PHOTO LIBRARY

FIGURE 13.7.2 Without an atmosphere, air resistance and buoyancy do not affect a hammer or feather. Both fall at the same rate towards the Moon's surface.

INQUIRING FURTHER

Compare the difference between the buoyancy force and air resistance as applied to a feather and a hammer respectively.

13.7.2 Buoyancy

The effect of Earth's gravitational field, the gravitational acceleration, gets smaller the greater the distance from Earth; nevertheless, for distances somewhat above where aeroplanes usually fly, the change is very slight. The difference between the Earth's gravitational field at the ground and well beyond is, therefore, regarded as negligible. An object falling down will gain 9.8 metres per second every second, reaching 35 km h^{-1} after 1 second. After the next second, it will be falling with twice that speed (19.6 m s^{-1}; 70 km h^{-1}). After 10 s an object would be falling at 98 m s^{-1} (350 km h^{-1}).

Objects falling directly downwards

When analysing the motion of a falling object, we use the following conventions:

- The origin is the point at which the object starts to move.
- Downwards direction is positive.
- *suvat* variables are all positive, including $a = g = {}^{+}9.8\ \text{m s}^{-1}$.

WORKED EXAMPLE 13.7.1

A watch falls from a Sydney Harbour Bridge climber's wrist. It takes 2.5 s before hitting a car below.

a Sketch a velocity–time graph of this motion.

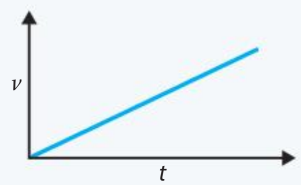
b Calculate the velocity with which the watch hits the car.

c Calculate the distance the watch falls.

d Show how these results can be obtained by using only the graph in part **a**.

ANSWERS

a



b $s = ?,\ u = 0\ \text{m s}^{-1},\ v = ?,\ a = {}^{+}9.8\ \text{m s}^{-2},\ t = 2.5\ \text{s}$

$v = u + at$

$\Rightarrow v = 0\ \text{m s}^{-1} + 9.8\ \text{m s}^{-2} \times 2.5\ \text{s}$

$\Rightarrow v = +24.5\ \text{m s}^{-1}$ (down is positive)

c $s = ?,\ u = 0\ \text{m s}^{-1},\ v = 24.5\ \text{m s}^{-1},\ a = {}^{+}9.8\ \text{m s}^{-2},\ t = 2.5\ \text{s}$

$$s = ut + \frac{1}{2}at^2$$

$$s = 0\ \text{m} + \frac{1}{2} \times {}^{+}9.8\ \text{m s}^{-2} \times (2.5\ \text{s})^2$$

$\Rightarrow s = 31\ \text{m}$

d Gradient, $g = \dfrac{v}{t}$

$\Rightarrow v = gt$

$\Rightarrow v = {}^{+}9.8\ \text{m s}^{-2} \times 2.5\ \text{s}$

$\Rightarrow v = {}^{+}24.5\ \text{m s}^{-1}$

area, $s = \dfrac{1}{2}vt$

$$\Rightarrow s = \frac{1}{2} \times 24.5\ \text{m s}^{-1} \times 2.5\ \text{s}$$

$\Rightarrow s = 31\ \text{m}$

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Objects projected directly upwards to top of flight

When analysing the motion of a vertically projected object, we use the following conventions:

- The origin is the point at which the object starts its motion.
- The upwards direction is positive.
- Acceleration is downwards: $a = {}^{-}9.8\,\text{m s}^{-2}$.
- The *suvat* variables are positive if directed upwards and negative if directed downwards.

WORKED EXAMPLE 13.7.2

A firework ball is launched directly upwards with an initial speed of $35\,\text{m s}^{-1}$. It explodes at the highest position reached.

a Sketch the v versus t graph for the firework ball until it explodes.

b Find the height at which the firework ball explodes.

c Find the time it takes from launch until the firework ball explodes.

ANSWERS

a The velocity–time graph is shown in Figure 13.7.3.

b Solution by graphical model

See Figure 13.7.3. The graph enables the solution to be calculated 'by gradient' and 'by area'. It relies on the known gradient (${}^{-}9.8\,\text{m s}^{-2}$) and the area of a triangle. It is a simpler, quicker solution than the algebraic method shown below.

Solution by algebraic model

$s = ?,\ u = 35\,\text{m s}^{-1},\ v = 0\,\text{m s}^{-1},\ a = {}^{-}9.8\,\text{m s}^{-2},\ t = ?$

$$v^2 = u^2 + 2as$$

$$s = \frac{v^2 - u^2}{2a}$$

$$\Rightarrow s = \frac{(0\,\text{m s}^{-1})^2 - (35\,\text{m s}^{-1})^2}{2 \times {}^{-}9.8\,\text{m s}^{-2}}$$

$$\Rightarrow s = 63\,\text{m}\ (62.5\,\text{m})$$

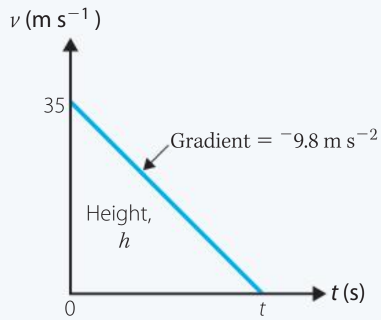
c $s = 62.5\,\text{m},\ u = 35\,\text{m s}^{-1},\ v = 0\,\text{m s}^{-1},\ a = {}^{-}9.8\,\text{m s}^{-2},\ t = ?$

$v = u + at$

$$\Rightarrow t = \frac{v - u}{a}$$

$$\Rightarrow t = \frac{0\,\text{m s}^{-1} - 35\,\text{m s}^{-1}}{{}^{-}9.8\,\text{m s}^{-2}}$$

$$\Rightarrow t = 3.6\,\text{s}$$



By gradient:

$$\text{Gradient, } a = \frac{0\,\text{m s}^{-1} - 35\,\text{m s}^{-1}}{t - 0\,\text{s}} = {}^{-}9.8\,\text{m s}^{-2}$$

$$\Rightarrow t = \frac{35\,\text{m s}^{-1}}{9.8\,\text{m s}^{-2}} = 3.6\,\text{s}$$

By area:

$$s = \frac{1}{2}t \times 35 = h$$

$$h = \frac{1}{2}(35\,\text{m s}^{-2} \times t)$$

$$\Rightarrow h = \frac{1}{2} \times 35\,\text{m s}^{-1} \times 3.6\,\text{s}$$

$$\Rightarrow h = 63\,\text{m}$$

FIGURE 13.7.3

Object projected directly upwards then falls back down

By symmetry, for a projectile falling back to the same place from which was launched:

$$v = -u$$

The acceleration due to the gravitational field is always the same. It cannot be turned off. This is always true, no matter whether the object's velocity is directed upwards (positive), downwards (negative) or momentarily stopped at the top position. Remember, for as long as the object is above the ground, the acceleration due to the gravitational field is constant: $g = {}^{-}9.8\,\text{m s}^{-2}$, downwards.

The result of this is that when the velocity is upwards, the object's speed is decreasing. It will stop momentarily at the highest point of the flight. Then, its speed will start to increase as it begins to fall back down again. The momentary stop does not cause gravity to turn off. At the top, the instantaneous *change* in velocity is always ${}^{-}9.8\,\text{m s}^{-2}$, even if the instantaneous velocity is zero. At every instant, including for the instant of time at the top of the flight, the velocity is *changing*.

WORKED EXAMPLE 13.7.3

An arrow is fired vertically upwards with an initial speed of $18.8\,\text{m s}^{-1}$. It lands next to the place from which it was launched.

a Sketch a velocity versus time graph for this motion.

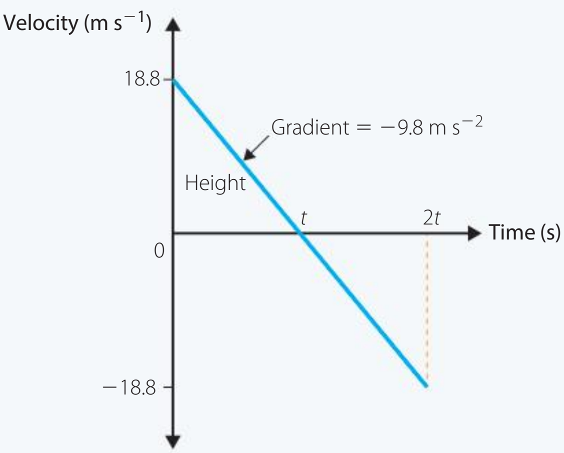
b Find the time for which the arrow remains in flight.

c Find the maximum height reached by the arrow.

d Compare the distance and the displacement of the arrow at the end of its flight.

ANSWERS

a



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b Solving graphically

$$\text{gradient}, g = \frac{v}{t}$$

$$\Rightarrow t = \frac{v}{g}$$

$$\Rightarrow t = \frac{18.8\ \text{m s}^{-1}}{9.8\ \text{m s}^{-2}}$$

$$t = 1.92\ \text{s}$$

By symmetry, $T = 2t$

$\Rightarrow T = 2 \times 1.92\ \text{s}$

$\Rightarrow T = 3.84\ \text{s}$

Solving algebraically

$s = ?,\ u = 18.8\ \text{m s}^{-1},\ v = 0\ \text{m s}^{-1},\ a = {}^{-}9.8\ \text{m s}^{-2},\ t = ?$

$v = u + at$

$$\Rightarrow t = \frac{v - u}{a}$$

$$\Rightarrow t = \frac{0\ \text{m s}^{-1} - 18.80\ \text{m s}^{-1}}{{}^{-}9.8\ \text{m s}^{-2}}$$

$$\Rightarrow t = 1.92\ \text{s}$$

$$t = 1.92\ \text{s}$$

By symmetry, $T = 2t$

$\Rightarrow T = 2 \times 1.92\ \text{s}$

$\Rightarrow T = 3.84\ \text{s}$

c Solving graphically

height, h_{top} = area to 't'

$$\Rightarrow h_{top} = \frac{1}{2} \times 18.8\ \text{m s}^{-1} \times 1.92\ \text{s}$$

$$\Rightarrow h_{top} = 18\ \text{m}$$

Solving algebraically

$s = ?,\ u = 18.8\ \text{m s}^{-1},\ v = 0\ \text{m s}^{-1},\ a = {}^{-}9.8\ \text{m s}^{-2},\ t = 1.92\ \text{s}$

$$v^2 = u^2 + 2as$$

$$\Rightarrow s = \frac{v^2 - u^2}{2a}$$

$$\Rightarrow s = \frac{(0\ \text{m s}^{-1})^2 - (18.80\ \text{m s}^{-1})^2}{2 \times ({}^{-}9.8\ \text{m s}^{-2})}$$

$$\Rightarrow s = {}^{+}18\ \text{m}$$

d Displacement:

$$\vec{s} = \vec{d}_2 - \vec{d}_1 = 0\ \text{m} - 0\ \text{m} = 0\ \text{m}$$

Distance:

$$s = \left|\vec{d}_2 - \vec{d}_1\right| + \left|\vec{d}_1 - \vec{d}_2\right|$$

$$\Rightarrow s = \left|{}^{+}18\ \text{m} - 0\ \text{m}\right| + \left|0\ \text{m} - {}^{-}18\ \text{m}\right|$$

$$\Rightarrow s = 36\ \text{m}$$

SECTION REVIEW 13.7

REMEMBERING

1 Define:

- a gravitational force
- b gravitational acceleration
- c 'near Earth'.

2 State the magnitude of the gravitational acceleration near Earth.

UNDERSTANDING

3 Describe and explain the conditions for which the gravitational acceleration near Earth' surface is usually taken to be:

- a positive
- b negative.

APPLYING

4 A rock dropped from a cliff hits the ocean with a speed of 44.1 $m\,s^{-1}$.

- a Sketch the velocity versus time graph for this motion.
- b Find the time taken for the rock to fall to the ground.
- c Find the height of the cliff.
- d Show how these results can be obtained by an alternative method (graphical or algebraic representation) to the one you used to solve part **b** and part **c**.

5 Jan stands exactly 5.0 m vertically below a window. She throws a set of keys vertically upwards so that the keys are stationary when level with the windowsill.

- a Find the time taken for the keys to reach the windowsill.
- b Determine the speed with which Jan should throw the keys.

REFLECTING

6 For vertical projectile motion, evaluate your responses to the following statements and suggest ways to improve your skills if necessary:

- a 'I readily understand and can use positive and negative values for the gravitational acceleration.'
- b 'I am confident that I use both algebraic and graphical solution methods with ease.'

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13.8 Mandatory practicals: finding the value of gravitational acceleration and determining launch velocity

PRACTICAL ACTIVITY 13.8.1

Gravitational acceleration

For a falling object not affected significantly by air resistance, the value of the gravitational acceleration, g, can be found by collecting first-hand information.

AIM

To find the value of the gravitational acceleration, g

MATERIALS

- ruler
- ball bearing
- electronic timer or timing photogate

WHAT ARE THE RISKS IN DOING THIS EXPERIMENT?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
The ball bearing may cause injury if thrown, dropped or stood on.	Never throw ball bearings. Manage the use of the ball bearing carefully. Never leave the ball bearing lying on the ground.

RISK ASSESSMENT

PROCEDURE

1. Set up the electronic timing apparatus.
2. Carefully measure the vertical distance, s, that the ball bearing will fall.
3. Use the timing apparatus to measure the time, t, taken for the ball bearing to fall through the known vertical height when released from rest from the upper position.
4. Repeat this several times.
5. Change the height of fall and repeat the procedure.
6. Record sufficient data to plot a graph.

RESULTS

1. Record all raw and derived data in a correctly constructed data table.
2. Plot the data as it is collected.
3. Estimate and record uncertainties in the data.

ANALYSIS OF RESULTS

1. Plot s versus t_{av}, showing uncertainty bars.
2. Draw a line of best fit.
3. From the line of best fit, construct a data table of data points, (t_{av}, s). Add an extra column for $(t_{av})^2$.
4. Plot s versus $(t_{av})^2$.
5. Draw a straight line of best fit and calculate the gradient.
6. Show that the equation $s = ut + \frac{1}{2}at^2$ can be used to find the acceleration from the gradient of the s versus $(t_{av})^2$ graph.

7 Justify the best estimate of the value of the acceleration due to gravity, g, found in this experiment.

8 Use the least and greatest possible values of the gradient of the s versus $(t_{av})^2$ graph to estimate the uncertainty in the experimental value of g. (Do not use the regression equation from your calculator!)

DISCUSSION

1 Suggest ways in which this experiment could be made to be more accurate.

2 Evaluate the reliability of this procedure by analysing the variation in the separate measurements of time taken by the ball bearing before the average was found.

3 Suggest why a ball bearing was used rather than a tennis ball or other similar object.

CONCLUSION

1 Summarise the experiment in one or two sentences.

2 Provide a precise value for g (best estimate ± uncertainty limits).

3 Identify at least two difficulties you had when undertaking this experiment.

4 Describe changes that could be made to overcome these difficulties.

PRACTICAL ACTIVITY 13.8.2

Launch velocity

The time of flight of a projectile can be used to calculate its initial velocity if other variables are known.

AIM

To find the initial vertical velocity of a launched projectile

MATERIALS

- apparatus that will launch an object vertically
- video camera or similar
- ruler or measuring tape

RISK ASSESSMENT

WHAT ARE THE RISKS IN DOING THIS EXPERIMENT?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
Some objects and launch speeds may pose a risk to eyes and faces.	Wear safety glasses. Do not put your face over the launcher.

PROCEDURE

1 Arrange the apparatus so that the object is launched vertically from the edge of a desk or benchtop, and lands on the floor beside the desk, as shown in Figure 13.8.1.

2 Measure s, the displacement of the object from its launch position.

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3 Launch the object and record its motion until it hits the ground.

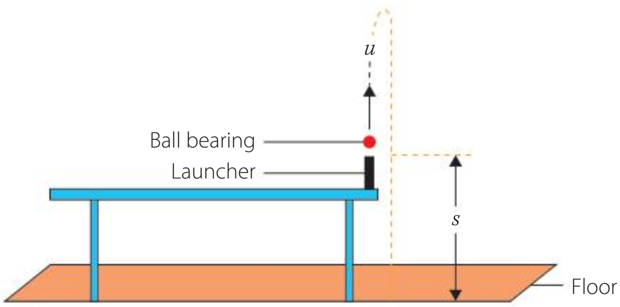

FIGURE 13.8.1 Experimental arrangement

RESULTS

1. Use the recording to produce s–t, v–t and a–t graphs for the motion.
2. Estimate the uncertainty in each of the data points and show these on your graphs.
3. Repeat the experiment for a different launch speed but the same final displacement.

ANALYSIS OF RESULTS

1. Describe the main features of each of the graphs. Include, where appropriate, the meaning of the:
   a. y intercept
   b. gradient
   c. area under the graph.
2. Explain how to use the graphs to find the:
   a. initial speed
   b. acceleration due to the gravitational field.
3. State, with an appropriate estimate of the uncertainty, the value of the:
   a. initial speed
   b. the acceleration due to the gravitational field, g.

DISCUSSION

1. Compare the value of g found in this experiment with the accepted value of g and its uncertainty at your latitude (see Figure 13.7.1, page 279). Explain whether your experiment confirmed or did not confirm the accepted value of g, within the uncertainty of the data.
2. Explain how the experimental data-collection method could be improved in order to increase the level of confidence in the launch speed reported.

CONCLUSION

1. Write a short sentence that describes the purpose of, and the method used in, this experiment.
2. State the precise value of the initial speed of the projectile.
3. Indicate any other worthwhile data, such as maximum height attained and value of g, that were found during the experiment.

CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 Define the following and include definitions of all symbols used.

a Distance and displacement

b Speed and velocity

c Acceleration

2 Write down the *suvat* formulas, define each term and explain how they can be used to find all the measureable kinematic variables.

3 Describe how area and gradient are used to find kinematic quantities.

CATEGORY QUESTIONS

4 Compare and contrast instantaneous and average:

a speed

b velocity

c acceleration.

5 In vertical motion, the value of g is generally taken to be negative. Explain. Discuss conditions under which g might be taken to be positive. Show these conditions on separate v–t graphs.

ELABORATION QUESTIONS

6 'For kinematics, graphs and algebraic formulas are identical.' Discuss.

7 As a blue car moving at a constant 18 m s^{-1} passes a stationary red car, the red car begins to move with a constant acceleration of 3.0 m s^{-2}.

Use a graphical solution to show when the two cars are next to each other again.

8 A 0.25 kg firework explodes at a height of 50 m above the launch point. Compare the launch speed of this firework with that of a 0.50 kg firework that explodes at 25 m above the launch point. Discuss whether or not the mass affected the answer.

EVIDENCE QUESTIONS

9 'If the braking distance for a car travelling at 40 km h^{-1} is 15 m, the braking distance at 80 km h^{-1} increases by 4 times to 60 m.'

Explain, using a graphical approach, how the following quantitative values were determined.

a Braking time

b Assumed acceleration used in these cases

c Stopping time and stopping distance when a realistic reaction time is factored into the calculations

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END-OF-CHAPTER EXAM

End-of-chapter test

PHYSICS

1 A particle moves from $^{+}1.23$ mm to $^{+}62.7$ μm. The change in displacement is closest to:

A $^{+}63.93$ mm.

B $^{-}61.5$ μm.

C $^{-}1.17 \times 10^{-3}$ m.

D $^{-}0.12$ cm.

2 Instantaneous and average speed are the same only for:

A time intervals that are negligible.

B distance intervals that are negligible.

C velocity intervals that are negligible.

D constantly accelerated motion.

3 For a speed–time graph, the gradient and area can be used to determine, respectively:

A acceleration, velocity interval.

B position, distance interval.

C change in velocity, acceleration.

D acceleration, position.

4 A particle accelerates uniformly from rest to a speed of 8.0 m s^{-1} in 2.0 s. It continues to accelerate at the same rate. What is its speed after 5.0 s?

A 16.0 m s^{-1}

B 20.0 m s^{-1}

C 32.0 m s^{-1}

D 40.0 m s^{-1}

5 An object accelerates at 6.0 m s^{-1} from rest. How far does it travel in the first 3.0 s?

A 2.0 m

B 9.0 m

C 18 m

D 27 m

6 An object is launched vertically upwards at a speed of 5.0 m s^{-1}. How long does it take to return to the launch site?

A 3.92 s

B 1.96 s

C 1.02 s

D 0.51 s

7 The area under an acceleration–time graph is used to find the change in ______________.

8 Calculate the displacement interval between these initial and final positions (showing your working).

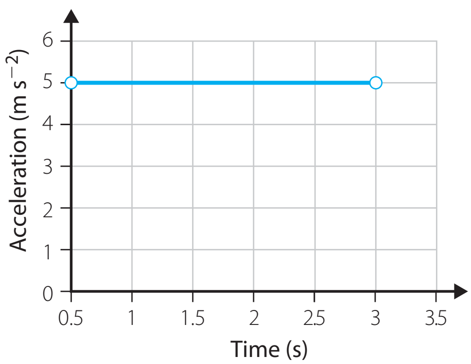
a $^{+}15.1$ m and $^{-}4.3$ m

b $^{-}6.75 \times 10^{-3}$ m and $^{+}250$ μm

9 Compare instantaneous and average velocity.

10 For a falling object, the acceleration is $^{+}9.8\ \text{m s}^{-2}$ when the change in distance is measured from the ______________.

11 The graph below shows the acceleration of a car that was initially travelling at $18\ \text{m s}^{-1}$.



a Find the change of speed between 0.5 s and 1.0 s of the car's motion.

b Calculate the speed of the car after 3.0 s.

12 Explain why it is necessary to define a frame of reference in order to find displacements, giving an example from your work in class.

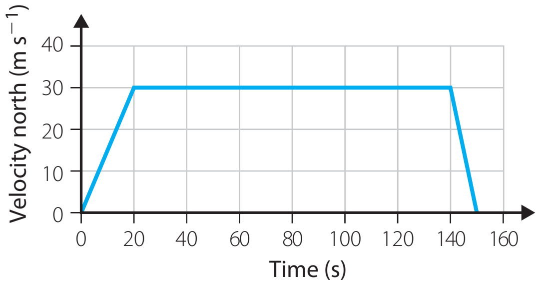
13 Explain how a moving object can have a negative acceleration but still be travelling forwards in the positive direction.

14 Given the three kinematic variables s, u and t, explain how it is possible to calculate the other two variables, v and a.

15 A horse and rider are 5.0 km east of a homestead. Five hours later they are 35 km west of the homestead. Calculate the average speed of horse and rider. Give the answer in m s^{-1}.

16 A firework is projected upwards at a speed of $20\ \text{m s}^{-1}$. A little later at 1.2 s, it has a speed of $8.24\ \text{m s}^{-1}$. Find the position of the firework after 1.2 s.

17 The graph that follows shows how a fast train accelerates uniformly from rest to $30.0\ \text{m s}^{-1}$ in 20 s. It then travels for 120 s at $30.0\ \text{m s}^{-1}$ before coming uniformly to a stop in 10 s.



a Find the distance travelled by the train in the first 25 s.

b Calculate the total distance travelled.

c Determine the acceleration of the train at 125 s.

d Find the time taken for the train to travel 300 m.

18 A rocket is launched vertically upwards with a speed of 30 m s^{-1} from the top of a cliff.

a Calculate the maximum height reached.

b Calculate the time it takes the rocket to reach the maximum height.

c Determine the time for which it was 40 m above the cliff.

19 Explain why displacement and time are always measures of change or interval.

20 Explain why measures of position and time are all that are necessary to describe motion.

21 A car is being driven at speed v when the driver notices a dangerous obstacle at distance d on the road ahead. After reaction time t, the driver applies the brakes to decelerate uniformly. The car comes to a stop just before the obstacle in a stopping time of T.

a Draw a graph of this situation.

b Use the graph to show that the stopping distance, D, can be given by the expression $D = vt + \frac{v^2}{2a}$.

c Near a school a car travels at 12 m s^{-1}, which is just above the speed limit. If the car can decelerate at 6.0 m s^{-2}, and the normal reaction time is 0.2 s, find the stopping distance, D.

d In the context of the school zone, discuss the effect of distraction and higher speed on the reaction distance. In your answer, refer to the equation in part b.

14 FORCES

Introduction

Athletes push against the ground to run and jump. They throw balls and strike them with bats to make them change direction and speed. They lift weights by pushing against gravity. Gymnasts pull on ropes and bars. Muscles push and pull in order to run and jump, throw and strike and lift. Pushes and pulls are forces applied to objects. An understanding of forces is therefore crucial to understanding how to perform better as an athlete.

Stimulus question

Can physics help athletes perform better?

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14.1 Forces acting on an object

FIGURE 14.1.1 Isaac Newton said in 1676, 'If I have seen further, it is by standing on the shoulders of giants.'

Forces are external actions applied by objects on objects. Objects do not own a particular force inside them. Force can be applied by direct physical contact, a **contact force**, or over a distance, a **non-contact force**, including through a vacuum. This distinction is a useful starting point. At a more basic level, all forces turn out to be non-contact, or **action-at-a-distance forces**. Forces – pushes or pulls – affect the motion of objects. Force has a magnitude and a direction; therefore, force is a vector.

Forces affect the motion of objects. Isaac Newton (1643–1727) pioneered a way of understanding everyday forces and their effects. He built his understanding on developments that had evolved over centuries in the study of astronomy and movement (Figure 14.1.1).

To understand motion, consider a very simple case: a single point mass object subjected to a single external force. The state of motion of the object changes when a force is applied to it. If it is stationary, it will start to move. If it is moving, it will speed up, slow down or change direction. Both speed and direction may change simultaneously when a force is applied. When this object collides with another object, it will apply a force. At the same time, the second object will apply a force to the first one.

contact force
force applied by one object on another when they are separated by such a small distance that they appear to be touching

non-contact force
force applied by one object on another when they are separated by distance

action-at-a-distance forces
a non-contact force

Forces are applied externally by agents on receivers

Force is applied by one object on another object. Neither object has a particular amount of force inside it. Strictly speaking, it is incorrect to talk about 'the force of an object'. 'Force of' suggests that an object owns a particular amount of force. It is obvious that the same object may apply a large force on one object and a small force on another object. How then could it have or own a particular single force?

The interaction between objects reveals the forces applied. A force is always applied externally by something (the agent) on something else (the receiver). We write:

$$F(\text{by agent on receiver})$$

The interaction between objects is mutual:

- Object A exerts a force on object B: $\vec{F}$(by A on B).
- Object B exerts a force on A: $\vec{F}$(by B on A).

Note that the decision about which object is the agent and which object is the receiver depends on the particular object of interest. Usually, the object of interest is treated as the receiver.

KEY FORMULA

Force nomenclature

Object A exerts a force on object B:

$$\vec{F}(\text{by A on B})$$

Object B exerts a force on A:

$$\vec{F}(\text{by B on A})$$

Types of forces

As a first approximation, a distinction can be made between contact forces and non-contact forces.

Contact forces

Contact forces are forces that involve two objects that appear to be touching each other.

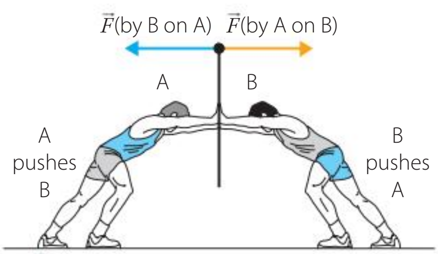

FIGURE 14.1.2 Person A contacts person B, so A acts on B: $\vec{F}$(by A on B). At the same time, B contacts A, so B acts on A: $\vec{F}$(by B on A).

SYLLABUS LINK

Nelson QScience Physics Units 3 & 4 discusses the concept of fields, non-contact forces and the way forces are mediated by fields.

Non-contact forces

Non-contact forces occur when objects that are clearly not touching experience a force. These non-contact forces are also known as 'action-at-a-distance' forces. The three most familiar non-contact forces are the electrostatic force, the magnetic force and the gravitational force.

Electrostatic force

Every charged particle exerts an electrostatic force on every other charge. Charge comes in two forms: positive and negative. Charged particles will repel each other if they carry the same sign. Two oppositely charged objects will attract (Figure 14.1.3). Electrostatic force is responsible for the way dry hair stands up when being combed, why sparks are seen when undressing in the dark, and lightning.

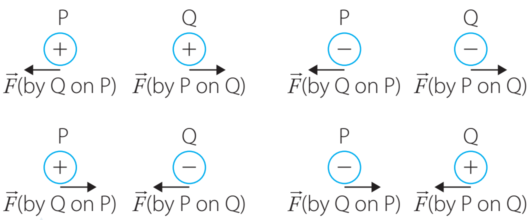

FIGURE 14.1.3 Charge P and charge Q apply action-at-a-distance forces on each other. The forces are repulsive if the charges on P and Q have the same sign and attractive if P and Q are oppositely charged.

TABLE 14.1.1 Charges of the same sign repel; charges of different signs attract

	⊕	⊖
⊕	Repel	Attract
⊖	Attract	Repel

Magnetic force

A magnet is an extended object that applies a magnetic force on other magnets and magnetic materials. Earth can be modelled as a very large magnet. The poles of a magnet are called north and south poles. This is determined by reference to the general direction to which they point when allowed to swing freely near the Earth. A north pole is a north-seeking pole that points more or less towards Earth's geographic north, and a south pole points more or less towards Earth's geographic south. The direction the magnet points is determined by the direction of the Earth's magnetic field.

When two magnets are brought near to each other, opposite poles attract and like poles repel.

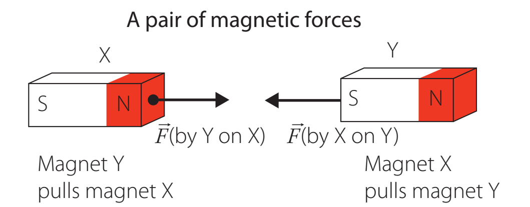

FIGURE 14.1.4 A pair of magnetic forces; opposite poles attract.

TABLE 14.1.2 Like magnetic poles repel; unlike magnetic poles attract

	NORTH POLE	SOUTH POLE
NORTH POLE	Repel	Attract
SOUTH POLE	Attract	Repel

Gravitational force

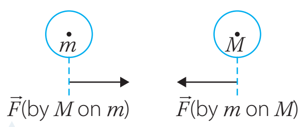

FIGURE 14.1.5 Two masses are mutually attracted.

Every mass exerts a gravitational force on every other mass. For example, two small isolated masses, m and M, far out in space are gravitationally attracted; mass m attracts mass M, and mass M attracts mass m.

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Earth's gravitational force

Earth's mass applies an observable gravitational force on masses such as the Moon, satellites and things on the surface. It is an action-at-a-distance or non-contact force because the masses are clearly not touching, yet a force is being applied.

14.1.1 What is gravity?

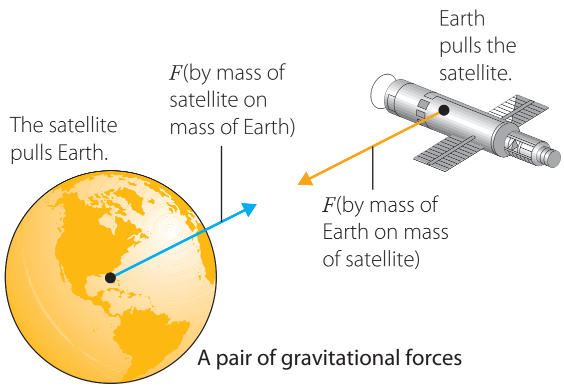

FIGURE 14.1.6 Gravitational force is an action-at-a-distance force. The mass of the Earth attracts the mass of the satellite. Simultaneously, the mass of the satellite attracts the mass of the Earth.

The very large mass of the Earth applies a gravitational force on the much smaller masses situated on the Earth. In everyday language, this force is called **gravity**, but it is usual for physicists to speak of gravitational force by mass on mass more generally.

Mass of Earth (agent) acts on a very much smaller mass (receiver):

$$\vec{F}(\text{by mass of Earth on mass of object})$$

This is the force we are usually interested in.

The smaller mass also exerts a gravitational force on the larger mass:

$$\vec{F}(\text{by mass of object on mass of Earth})$$

Usually, we are not concerned about the effects of the smaller mass on the Earth's mass.

gravity gravitational force applied by Earth's mass on smaller masses on or near Earth; by extension, the force applied by a large celestial mass, such as a moon or a planet, on nearby masses

weight gravitational force on mass; force exerted by mass of Earth on masses 'near Earth'; by extension, force by any large mass in the universe, such as the Moon, on any smaller mass 'nearby'

Weight

On Earth, the term '**weight**' is used to mean the gravitational force applied by the mass of Earth on a much smaller mass, for example a person.

Weight is a force, measured in newtons. It is not a mass, which is measured in kilograms. This can be confusing. Typical bathroom scales measure the weight force applied to them. The scale is then converted to read the mass that would experience that force, on Earth. For example, a 60 kg person applies a 588 N force on the weighing machine. The weighing machine measures a force of 588 N and converts it to 60 kg on the scale. The person would then say they have a weight of 60 kg. Strictly speaking, the person has a mass of 60 kg and exerts a force on the weighing machine equivalent to the force due to gravity – the force applied by the mass of Earth – on a 60 kg mass. Be careful to ensure everyday language does not affect the way you understand physics ideas.

KEY FORMULA

$$\vec{w} = \vec{F}(\text{by mass of Earth on mass of object})$$

Where:

$\vec{w}$ = weight force

No object has a weight, because that would mean that an object contains a force, which is incorrect; objects do have mass, however, because that is a measure of their substance.

If the 60 kg person and the weighing machine were taken to the Moon, the scale would show that the person weighs about 10 kg. This is because the Moon exerts a gravitational force that is about one-sixth the gravitational force applied by Earth. The person does not lose any of their substance, their mass, by travelling to the Moon. They must still have 60 kg of substance. But the force applied by the mass of the Moon on a 60 kg mass is equivalent to the force applied to a 10 kg mass on Earth.

14.1.2 Gravity and the human body

SCIENCE AS A HUMAN ENDEAVOUR

DEVELOPMENTS IN THE STUDY OF FORCE

Our modern concept of force was developed over thousands of years. Careful thought, observation and measurements concerning motion on Earth and planetary motion caused lively debate during the 16th and 17th centuries. Older ideas gave way to simpler, better understanding of force, especially gravitational force. Gravitational force has still not been fully explained. It is still an important research topic.

Research the work of these significant people who affected our understanding of motion:

1 Aristotle (384–322 BCE)

Aristotle's ideas include natural motion, natural cause, efficient cause and violent cause. He argued that a net force caused constant speed (a common misconception even today).

2 Ptolemy (100?–170?)

Ptolemy produced a geocentric (Earth-centred) model of planetary motion, including epicycles, using Aristotle's ideas about motion. Geocentric coordinates, but not epicycles, are still used today for many applications.

3 Copernicus (1473–1543)

Copernicus published a heliocentric (Sun-centred) model of planetary motion, which depended significantly on observations made by the Islamic astronomer Al Battani (858–959). Later observations and explanations by Tycho Brahe (1546–1601) and Johannes Kepler (1571–1630) were influential in supporting Copernicus' ideas and undermining Ptolemy's system.

4 Galileo (1564–1642)

Galileo produced a heliocentric model of planetary motion similar to that of Copernicus, as well as telescopic observations that supported his model. He published a revolutionary book on the effects of forces on motion, including experiments on gravitational acceleration.

5 Newton (1643–1727)

Newton unified the laws of motion on Earth and in space through rigorous telescopic observations, acceptance of the heliocentric model and extraordinary insights into the laws of motion, including the universal law of gravity.

SECTION REVIEW 14.1

REMEMBERING

1 Describe three ways in which a force can affect the motion of a point mass.

2 Define the following terms.

a Contact force

b Non-contact force

c Electrostatic force

d Magnetic force

e Gravitational force

f Weight

3 When talking about force, what do the following terms mean?

a Agent

b Receiver

UNDERSTANDING

4 Explain why force is a vector.

5 'Strictly speaking, it is incorrect to talk about *the force of an object'* (page 293). Explain.

6 Two rugby players, Ben (B) and Matt (M), collide. Use the agent–receiver nomenclature to describe the forces involved in the interaction.

7 Explain the difference between mass and weight.

APPLYING

8 Compare the physical quantity that typical bathroom scales measure and the reading on the scale.

ANALYSING

9 A 30 kg box and the bathroom scales that were used to measure it were taken to the Moon. Explain why the box weighs about 5.0 kg on the Moon.

REFLECTING

10 Identify differences between your original thoughts about force and your current ideas after reading this section.

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14.2 Newton's three laws

Forces acting externally on stationary objects can cause them to move. The stationary object gains a non-zero velocity. A force applied externally on a moving object will change its speed, its direction of motion or both its speed and direction. Change of speed and change of velocity mean that the object accelerates. These ideas are not necessarily intuitive, but they are essential to have if motion and its causes are to be understood.

Newton summarised the causes of motion in three laws. These laws are not simply mathematical formulas to be remembered. They are a summary of a new way of thinking. Even today, many physics students think in old-fashioned, Aristotelian terms; that is, that forces are in objects or natural to objects and that forces cause things to move at uniform velocity, including zero velocity. Galileo and Newton overthrew Aristotelian thinking.

Newton's three laws relate to the sum of forces (net force) applied externally on a point mass.

Newton's first law

A force applied on a point mass will cause the point mass to change its velocity. If the mass is stationary, the force will cause it to start moving; the velocity of the mass will change. If the mass is already moving at constant velocity, the force will cause the velocity to change – speed will change (without change of direction) or direction will change (without change of speed), or speed and direction will both change simultaneously. That is, a body will not change its motion unless forced to do so. This is Newton's first law, which can be stated as:

A body will continue in its state of rest or of uniform motion in a straight line unless compelled by a net external force to change that state.

The emphasis in Newton's first law is on change of velocity. A change of velocity means acceleration. Thus, Newton's first law directs attention to the effect of force, namely, acceleration.

KEY FORMULA

In mathematical terms, Newton's first law can be written as follows:

If $\sum \vec{F}(\text{on receiver}) = 0$

then $\vec{a} = 0$

Where:

$\sum \vec{F}(\text{on receiver})$ = sum of forces on the receiver

From this, we can deduce that, if the acceleration of a mass is zero, the net force on that mass must be zero:

If $\vec{a} = 0$

then $\sum \vec{F}(\text{on receiver}) = 0$

Where:

$\sum \vec{F}(\text{on receiver})$ is the vector sum of all forces applied to the receiver object

$\vec{a}$ = the acceleration of the receiver

Inertia

The tendency of a body to continue in its state of rest or of uniform motion in a straight line is called inertia. It is a kind of resistance to the forces that would change the state of motion. Since inertial mass is the quantity that is resisting the change, 'inertial mass' and 'inertia' can be used interchangeably. A distinction is made between inertial mass and gravitational mass. Inertial mass is affected by external forces of all kinds. Gravitational mass is the mass of an object that acts at a distance on other masses via gravitational force. For current purposes, this distinction will not be pursued.

inertia, inertial mass tendency of a body to continue in its state of rest or of uniform motion in a straight line

gravitational mass mass of an object that acts at a distance on other masses via gravitational force

Newton's second law

The acceleration of a mass is affected by the net force applied to it as well as its inertial mass.

For a particular mass, *m*, the larger the net force, $\sum \vec{F}$, the greater the acceleration, *a*.

$$\vec{a} \propto \sum \vec{F}$$

For a given net force, the larger the mass, the smaller the acceleration:

$$\vec{a} \propto \frac{1}{m}$$

Altogether, the relationship between the dependent variable, $\vec{a}$, and the two independent variables, $\sum \vec{F}$ and m, is:

$$\vec{a} = \frac{\sum \vec{F}}{m}$$

KEY FORMULA

In mathematical terms, Newton's second law is expressed as:

$$\vec{a} = \frac{\sum \vec{F}}{m}$$

Where:

$\vec{a}$ = acceleration

$\sum \vec{F}$ = net force

m = mass

The constant of proportionality has been set at 1. The SI unit system has been constructed such that, by definition, a net force of 1.0 N applied to an inertial mass of 1.0 kg produces an acceleration of 1.0 m s^{-2}.

Newton's second law is just the mathematical expression of Newton's first law applied to a mass, m.

$$\text{If } \sum \vec{F} = 0, \quad \text{then } \vec{a} = 0.$$

$$\text{If } \vec{a} = 0, \quad \text{then } \sum \vec{F} = 0.$$

Newton's second law is also encountered in the algebraically equivalent statement:

$$\sum \vec{F} = m\vec{a}$$

This suggests that 'force' is 'mass times acceleration'. But this is untrue. It is obvious that a force is not two numbers multiplied together. It is true that a value for the magnitude of a force can be determined by calculating the product of mass and acceleration. Further, this form of the law incorrectly suggests that mass and acceleration cause force, since the net force is in the dependent variable position in the equation.

Acceleration due to gravity

Near Earth, every 1.0 kg of mass experiences the same force of 9.8 N.

An extended mass of 2.0 kg, for example, experiences two lots of 9.8 N of gravitational force, one lot of 9.8 N for each kilogram. The force on a 2.0 kg mass is therefore 19.6 N. The weight force applied to the 2.0 kg mass, colloquially known as 'the weight of the mass', is 19.6 N.

14.2.1 Gravity vs inertial mass

From Newton's second law:

$$a = \frac{F}{m}$$

$$\Rightarrow a = \frac{9.8 \text{ N}}{1.0 \text{ kg}}$$

$$\Rightarrow a = 9.8 \text{ m s}^{-2}$$

This is the constant acceleration due to gravity, g, that Galileo first identified by rolling balls down inclined planes. It was Newton's genius that extended gravitational analysis out into space. Nevertheless, to a good approximation for ordinary experience near the Earth, the acceleration due to gravity is constant.

$$g = 9.8 \text{ m s}^{-2}$$

The weight force, w, due to gravity that is applied on a mass is:

$$w = mg$$

KEY FORMULA

$w = mg$

Where:

w = weight force

m = mass

g = acceleration due to gravity

Newton's third law

Forces are only revealed in an interaction between two objects. The interaction involves forces of the same type: electrostatic, magnetic or gravitational. For two objects A and B, the interaction demonstrates the action of two forces: a force by A on B and, simultaneously, a force by B on A. The labels agent and receiver are applied differently depending on the object of interest. If we are interested in the effect of B on A, then B is the agent and A is the receiver. If we are interested in the effect of A on B, then A is the agent and B is the receiver.

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The forces are equal in magnitude but oppositely directed.

For convenience in the following text, Newton's three laws are referred to as Newton 1, Newton 2 and Newton 3.

KEY FORMULA

Newton's third law can be expressed as:

For every action there is an equal and opposite reaction.

When two objects A and B interact, the action–reaction pair of forces are:

$$F(\text{by } A \text{ on } B) \text{ and } F(\text{by } B \text{ on } A)$$

Four conditions must be satisfied for these to be an action–reaction or Newton 3 pair of forces:

- Same fundamental type
- Equal in magnitude
- Opposite in direction
- Act on different objects

The last criterion – that forces act on different objects – is especially significant. In many situations, the forces are equal in size and opposite in direction but act on the same object. This means that the net force on the object is zero. An action–reaction pair of forces cannot be added to each other to form a net force because they act on different objects: A acts on B and B acts on A.

SECTION REVIEW 14.2

REMEMBERING

1 Write each of Newton's three laws in words and symbols.

2 a List the four requirements that must be met for a pair of forces to be considered as an action–reaction pair.

b State the one condition that must be met for a net force to be identified.

UNDERSTANDING

3 a Describe inertia.

b Write the equation that connects mass and weight.

4 Explain what the symbol $\sum \vec{F}$ means.

5 Explain why an action–reaction pair of forces cannot be added together.

APPLYING

6 For some time during a 100 m sprint, an athlete runs at a constant 8.0 m s^{-1}. Describe the magnitude of the horizontal forces applied to the athlete.

ANALYSING

7 A basketball player jumps vertically to shoot. While the basketballer is in the air, gravity and air resistance are reduced to zero. Explain what would happen to the basketballer if the player was:

a on the way up

b on the way down

c at the top of the jump.

8 In the formula $a = k\frac{F}{m}$, $k = 1$. Explain.

9 Explain why the formula $a = \frac{F}{m}$ expresses the physical cause of motion better than its algebraic equivalent $F = ma$.

REFLECTING

10 Explain how your understanding of action–reaction forces and net force has developed.

14.3 Free-body diagrams

A free-body diagram is a model of forces acting on a point particle, which allows us to strip away all the surrounding aspects of an object and treat it as a single point. The forces applied on the object become the forces applied on the point. Arrows are used to indicate the direction and magnitude of the forces. There are three rules for force vectors on free-body diagrams:

- Tail starts at the point mass.
- Head points in the direction of the force.
- Length represents the magnitude.

Force on an object in one dimension

Free-body diagrams can be drawn in one-, two- or three-dimensions. We shall limit ourselves to one-dimensional motion; that is, motion along a straight line. In these circumstances we can use the positive and negative directions to represent the vector nature of forces and accelerations. This is entirely similar to the way we have analysed motion along a straight line from a kinematic point of view.

Standing and moving on a surface

Every object that is in contact with a surface applies a force on the surface and the surface applies a force on the object. These forces act at right angles to the surface. The force is an electrostatic force. For an object standing on the ground the electrostatic pair of action–reaction forces are:

$$F(\text{by object on surface})_{\perp}$$

$$F(\text{by surface on object})_{\perp}$$

Note the symbol $\perp$ in each case. The symbol means that the force is at right angles, or perpendicular, to the surface. All surfaces apply forces on objects that are at right angles to the surface. This perpendicular force is called the **normal force**, N.

normal force
force applied by surface at right angles (normal) to the surface

A person standing on a surface is not accelerating. This means that the net force on the person is zero. The net force applied on the person comprises the normal (electrostatic) force by the surface and the weight (gravitational) force:

$$\sum \vec{F}(\text{on person}) = N - w = 0$$

The normal force and the weight force are equal in magnitude and opposite in direction. Nevertheless, they are not an action–reaction pair of forces. The forces are not of the same type and they are not acting on different objects. Further, the normal force will be different for different masses located at that position on the surface. This means that the surface applies different forces in different circumstances. This demonstrates that the surface does not contain or own a particular force. It is this capacity of surfaces to provide different external forces on objects that enables you to jump up.

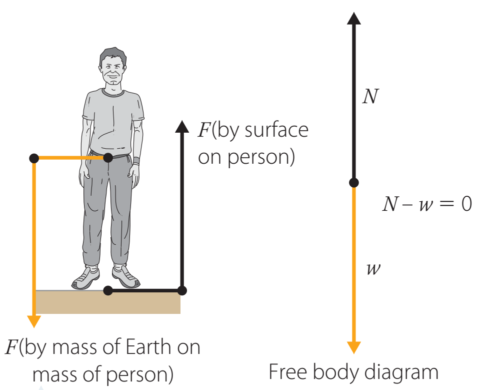

FIGURE 14.3.1 The forces applied to a person standing on the surface are the normal force and the weight force.

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Athletes and force

In jumping up vertically, an athlete pushes down on the surface. This increases the reaction or normal force applied on the athlete. There is a non-zero net force on the athlete because the athlete accelerates from the surface into the air. During the period of time when the athlete is in contact with the surface, the net force on the athlete includes the weight force on the athlete, w, and the normal force, N:

$$\sum \vec{F}(\text{on athlete}) = N - w > 0$$

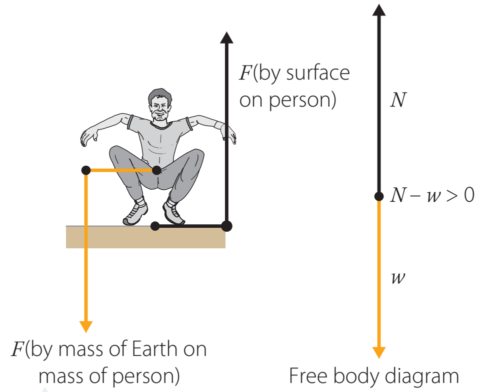

FIGURE 14.3.2 The forces applied by a surface on an athlete while in contact with the surface are the normal force and the weight force.

KEY FORMULA

$$\sum \vec{F}(\text{on athlete}) = N - w > 0$$

Where:

$\sum \vec{F}(\text{on athlete})$ = net force on athlete

N = force by surface on athlete perpendicular to the surface

w = weight force on athlete

friction force
force applied by a surface parallel to the surface

Subjectively, athletes know that they do the jumping because they do whatever it takes to push down as hard as possible. However, it is also true to say that 'the surface jumps the athlete', since it is the surface that provides the normal force large enough to overcome the gravitational force.

When an object moves horizontally, it applies a force on the surface and the surface applies a force on the object. These forces are an action–reaction pair that act parallel to the surface.

For an object moving parallel to a surface, the electrostatic pair of action–reaction forces are:

$$F(\text{by object on surface})_{||}$$

$$F(\text{by surface on object})_{||}$$

14.3.1 Principles of force in sport

The force on the object that is applied parallel to the surface is the **friction force**, f.

At the start to a sprint race, the athlete increases the friction force by pushing against the starting blocks. Consequently, the forwards reaction or friction force increases. Without the blocks it is more difficult to push against the surface of the track so as to ensure a large forwards friction force by the surface on the athlete. Note that it is the forwards frictional force by the surface on the athlete that causes the athlete to accelerate from the blocks.

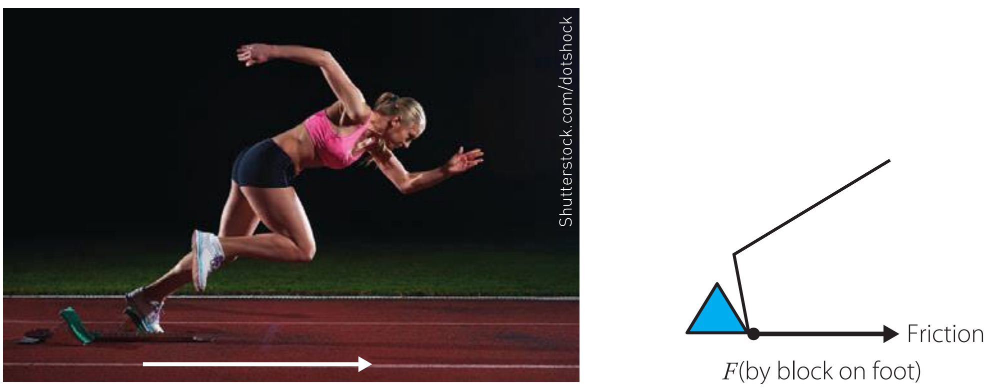

FIGURE 14.3.3 Sprint athletes increase friction by the surface by using starting blocks.

SECTION REVIEW 14.3

REMEMBERING

1 Define the following terms in words.
   a Free-body diagram
   b Normal force
   c Friction
2 Describe the rules for using vectors on free-body diagrams.
3 Name and identify the type of force that always acts at right angles to a surface.
4 Define in terms of agent and receiver.
   a The normal force, N
   b Friction, f

UNDERSTANDING

5 Explain why it is necessary to separate the force by the surface on an object into a force perpendicular to and a force parallel to the surface.
6 For one-dimensional motion, describe how the number line is used to represent force vectors.
7 For a person standing on a surface, explain why the weight force and the normal force are not an action–reaction pair, despite being equal in size and opposite in direction.

APPLYING

8 'Friction is the force that enables a person to walk.' Explain.
9 'The ground jumps you up.' Explain.

ANALYSING

10 Many people believe that friction always opposes motion. Is this true? Discuss.

14.4 Solving problems involving forces

When solving problems involving forces, follow the steps below:

- Read the question carefully.
- Visualise or sketch the situation described.
- Draw a free-body diagram.
- Identify each force acting on the object in question.
- Write each force in the form F(by A on B), or use the symbols provided in the question.
- If necessary, write the Newton 3 pair of forces.
- Identify the direction of the net force (or acceleration).
- Add any data provided in the question.
- Consider Newton's laws. Ask:
  - How does Newton's first law apply?
  - How does Newton's second law apply?
  - How does Newton's third apply?
- Set up any equations, using the symbols from the free-body diagram.
- Recall any kinematic formulas that may be useful; e.g. $a = \frac{v - u}{t}$.
- Solve the equations.
- Check to ensure the answers are those required.

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WORKED EXAMPLE 14.4.1

An 85 kg cyclist travelling at a constant speed of 12 m s^{-1} is subjected to 35 N of frictional resistance forces, f. Calculate and justify:

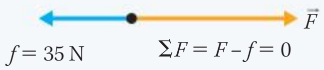
a the acceleration of the cyclist.

b the total forwards force by the cyclist, F(cyclist).

ANSWERS

a The acceleration is zero (Newton 1: at constant speed there is no change of velocity, hence zero acceleration).

b Draw the free-body diagram.



$\Sigma F = F - f = 0$

$F - 35\text{ N} = 0$

Newton 2:

$$\sum F = ma$$

$$F(\text{cyclist}) - f = 0\text{ N}$$

$$\Rightarrow F(\text{cyclist}) - 35\text{ N} = 0\text{ N}$$

$$\Rightarrow F(\text{cyclist}) = 35\text{ N}$$

WORKED EXAMPLE 14.4.2

At the start of a sprint race, an 85 kg runner pushes off the blocks and reaches a speed of 4.0 m s^{-1} after 0.40 s. Calculate the net force applied by the runner on the blocks. Justify your answer.

ANSWER

$m = 85$ kg

$v = 4.0$ m s^{-1}

$t = 0.40$ s

Newton 2:

$$F(\text{by blocks on runner}) = ma$$

$$\Rightarrow F(\text{by blocks on runner}) = 85\text{ kg} \times \frac{(4.0\text{ m s}^{-1} - 0\text{ m s}^{-1})}{0.40\text{ s}}$$

$$\Rightarrow F(\text{by blocks on runner}) = 85\text{ kg} \times 10\text{ m s}^{-2}$$

$$\Rightarrow F(\text{by blocks on runner}) = 850\text{ N}$$

Newton 3:

$$F(\text{by runner on blocks}) = F(\text{by blocks on runn}$$

$$\Rightarrow F(\text{by runner on blocks}) = 850\text{ N}$$

WORKED EXAMPLE 14.4.3

The feet of a 60 kg gymnast performing a vertical standing jump are on the floor for 0.25 s. The vertical speed attained at take-off is 3.5 m s^{-1}.

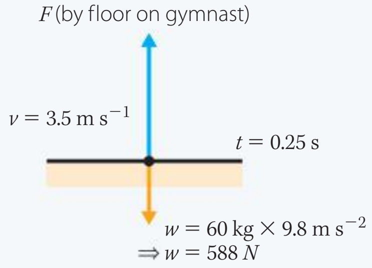
a Calculate the net force applied on the gymnast.

b Calculate the force applied by the floor on the gymnast.

c Find the force applied by the gymnast on the floor.

ANSWERS

a



Newton 2:

$$\sum F(\text{on gymnast}) = ma$$

$$\Rightarrow \sum F(\text{on gymnast}) = 60\text{ kg} \times \frac{(3.5\text{ m s}^{-1} - 0\text{ m s}^{-1})}{0.25\text{ s}}$$

$$\Rightarrow \sum F(\text{on gymnast}) = 60\text{ kg} \times 14\text{ m s}^{-2}$$

$$\Rightarrow \sum F(\text{on gymnast}) = 840\text{ N}$$

b Newton 2:

$$\sum F(\text{on gymnast}) = F(\text{by floor on gymnast}) - F(\text{by mass of Earth on gymnast})$$

$$\Rightarrow F(\text{by floor on gymnast}) - 60\text{ kg} \times 9.8\text{ m s}^{-2} = 840\text{ N}$$

$$\Rightarrow F(\text{by floor on gymnast}) - 588\text{ N} = 840\text{ N}$$

$$\Rightarrow F(\text{by floor on gymnast}) = 840\text{ N} + 588\text{ N}$$

$$\Rightarrow F(\text{by floor on gymnast}) = 1428\text{ N}$$

c Newton 3:

$$F(\text{by floor on gymnast}) = 1428\text{ N}$$

$$\Rightarrow F(\text{by gymnast on floor}) = 1428\text{ N}$$

SECTION REVIEW 14.4

REMEMBERING

1 Write down the steps to follow in order to solve problems involving forces.

UNDERSTANDING

2 A person jumps up vertically from the floor. Draw a free-body diagram to represent the forces applied to the person when their feet are:

a on the floor

b in the air.

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APPLYING

3 A 105 kg kayaker travelling at a constant speed of 4.0 m s^{-1} is subjected to 57 N of frictional resistance forces, *f*.
   a Calculate the total forwards force applied by the kayaker, *F*(by kayaker).
   b Calculate the acceleration of the kayaker.
   c Determine the normal force applied by the seat of the kayak on the kayaker.
4 A 50 kg box on a horizontal surface is being pulled by two people holding separate ropes. The tension in one rope is 50 N and it is 40 N in the other. The friction force by the surface on the box is 15 N.
   a Draw a free-body diagram to show this situation.
   b Calculate the net force on the box.
   c Find the acceleration of the box.
5 The acceleration of a 36 kg object sliding along a surface is 4.0 m s^{-2}. If the friction force is 12 N, calculate the force required.
6 A 70 kg diver takes 125 ms to jump up vertically from the 10 m high tower platform at a speed of 2.5 m s^{-1}.
   a Calculate the average acceleration of the diver during take-off.
   b Calculate the net force applied on the diver.
   c Determine the force applied by the diver on the high platform.
7 A 45 kg box sliding on a horizontal surface is subjected to a 15 N and a 30 N force to the right and a 10 N force to the left. There is a friction force of 5 N.
   a Draw a free-body diagram.
   b Calculate the net force on the box.
   c Calculate the acceleration of the box.
8 A 1.5 tonne load is attached to a cable and lifted. Calculate the force applied by the cable when the load is:
   a accelerated from start to 2.0 m s^{-1} in a distance of 5.0 m
   b lifted at 2.0 m s^{-1} for 15 s.

ANALYSING

9 Block A, of mass 2.0 kg, is touching block B of mass 3.0 kg. A third object, C, applies a force of 20 N to the right as shown in Figure 14.4.1.
   a Explain why the acceleration of the two blocks, block A and block B, is the same.
   b Calculate the acceleration of block A.
   c i Find *F*(by A on B).
     ii Find *F*(by B on A).

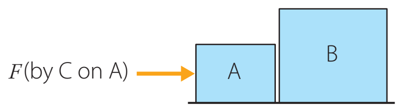

FIGURE 14.4.1

14.5 Conservation of momentum

It always takes time to exert a force on an object. For a particular force, the longer the time interval over which it acts, the greater the effect. The effect is the change in the velocity of the object. An analysis of Newton's second law shows how this works:

$$a = \frac{\vec{F}}{m}$$

$$\Rightarrow \frac{\vec{F}}{m} = \frac{\vec{v}}{t}$$

$$\Rightarrow \vec{F}t = m\vec{v}$$

Remember that the symbols $\vec{v}$ and t are intervals: change in velocity and change in time, respectively.

impulse
action of a force over a time interval; $\vec{J} = \vec{F}t$

momentum
quantity of motion calculated by the product of mass and velocity; $\vec{p} = m\vec{v}$

The quantity $\vec{F}t$ is called the **impulse** of the force, $\vec{J}$. It is the action of a force exerted over a time interval.

The quantity $m\vec{v}$ is the change of momentum of the body. **Momentum** is defined as the product of mass and velocity:

$$\vec{p} = m\vec{v}$$

For an object that is initially travelling at velocity $\vec{u}$, and which changes to velocity $\vec{v}$, caused by the impulse, $\vec{F}t$, the momentum change is:

$$\vec{p}_2 - \vec{p}_1 = m\vec{v} - m\vec{u}$$

In summary, the impulse of a force, that is, the effect of a force acting for a time interval, causes the momentum of an object to change.

KEY FORMULA

$\vec{J} = \vec{F}t$

Unit: newton second; N s

Where:

$\vec{J}$ = impulse of the force

$\vec{F}$ = force applied

t = time interval

KEY FORMULA

$\vec{p} = m\vec{v}$

Unit: kilogram metre per second; kg m s^{-1}

Where:

$\vec{p}$ = momentum

m = mass

$\vec{v}$, in this definition, is some generalised velocity

KEY FORMULA

$\vec{p}_2 - \vec{p}_1 = m\vec{v} - m\vec{u}$

Where:

$\vec{p}_1$ = initial momentum

$\vec{p}_2$ = final momentum

m = mass

$\vec{u}$ = initial velocity

$\vec{v}$ = final velocity

KEY FORMULA

Impulse = momentum change

Law of conservation of momentum

When two objects collide they transfer momentum. For two objects A and B that collide along a straight line, the number line sign convention is used to represent the vector nature of impulse and momentum. The arrows on top of the vectors can then be ignored.

In a system in which only the forces applied by the objects are considered – there are no external forces – the total momentum remains the same. This is the conservation of momentum law:

The total momentum in an isolated system is always the same.

KEY FORMULA

In an isolated system in which objects interact, the total initial momentum is equal to the total final momentum:

$$\sum \vec{p}_{\text{before}} = \sum \vec{p}_{\text{after}}$$

$$\Rightarrow \sum (m\vec{v})_{\text{before}} = \sum (m\vec{v})_{\text{after}}$$

Where:

$\sum \vec{p}_{\text{before}} = \sum (m\vec{v})_{\text{before}}$ = sum of momentum of system before objects interact

$\sum \vec{p}_{\text{after}} = \sum (m\vec{v})_{\text{after}}$ = sum of momentum of system after objects interact

m = mass

$\vec{v}$ = velocity of objects

The total momentum, p_T, does not change:

$$\vec{p}_{\text{T before}} - \vec{p}_{\text{T after}} = 0$$

Where:

$\vec{p}_{\text{T before}}$ = total momentum before interaction

$\vec{p}_{\text{T after}}$ = total momentum after interaction

For interactions along a straight line, the vector symbols can be ignored. Momentum change is then treated as positive and negative numbers.

Momentum conservation happens continuously throughout the interaction, because it is the impulse of the force that is exerted by each object on the other at any infinitesimally small instant of time that causes the change of momentum.

$$J(\text{by A on B}) = F(\text{by A on B})t$$

$$J(\text{by B on A}) = F(\text{by B on A})t$$

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The total momentum, P_T, in the system before the interaction is the sum of the initial momenta of A and B:

$$p_T = p_{Ai} + p_{Bi}$$

The total momentum, P_T, in the system after the interaction is the sum of the final momenta of A and B:

$$p_T = p_{Af} + p_{Bf}$$

Thus:

$$p_{Ai} + p_{Bi} = p_{Af} + p_{Bf}$$

By re-arranging this equality, the change of momentum for A and for B can be demonstrated:

$$p_{Af} - p_{Ai} = p_{Bi} - p_{Bf}$$
$$\Rightarrow p_{Af} - p_{Ai} = {}^{-}(p_{Bf} - p_{Bi})$$

The negative sign indicates that the change in momentum for object A is the opposite of the change in momentum for object B.

These momentum changes are produced by the impulse of the forces on each object. Thus:

$$F(\text{by B on A})t = {}^{-}F(\text{by A on B})t$$

This is just another way to state Newton's third law. Indeed, by dividing out the time interval, t, Newton's third law appears in either of the standard forms:

$$F(\text{by B on A}) = {}^{-}F(\text{by A on B})$$

or

$$F(\text{by B on A}) + F(\text{by A on B}) = 0$$

These are statements of Newton's third law, and we have already noted that the action–reaction pair cannot be added to form a net force. What is meant by this way of writing Newton's third law is that, through the impulse of the forces applied in the closed system, momentum is conserved. The division out of the time interval hides that fact.

PRACTICAL ACTIVITY 14.5.1

Law of conservation of momentum and Newton's third law

INTRODUCTION

A moving skateboard will slow down when a rider jumps sideways onto it. A stationary skateboard rider, A, will start to move, and a moving skateboard rider, B, will slow down when they collide and move off together.

The purpose of this practical activity is to demonstrate:

- the law of conservation of momentum
- Newton's third law quantitatively.

MATERIALS

- weighing scales
- 2 skateboards or equivalent carriages
- appropriate safety gear: helmet, knee pads, wrist pads
- motion sensors or video recording device

»

» Construct a table similar to the one below. Identify specific risks to a person's safety and ways to manage these risks.

RISK ANALYSIS

WHAT ARE THE RISKS IN DOING THIS INVESTIGATION?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?

PROCEDURE

1 Find and record the masses of the skateboards, rider A and rider B.

CONSERVATION OF MOMENTUM

1 Launch one skateboard so that it travels in a straight line at constant speed. This will require some practice.
2 Measure and record the constant speed of the skateboard.
3 Calculate and record the momentum of the skateboard.
4 Arrange for rider A to jump sideways onto the skateboard.
5 Measure the speed of skateboard plus rider.
6 Calculate and record the momentum of the skateboard plus rider.
7 Estimate any uncertainties in the data and their effect on the momentum calculation.
8 Repeat with rider B.

NEWTON'S THIRD LAW

1 Launch rider A on a skateboard towards stationary rider B on the second skateboard.
2 When A is alongside B, they take hold of each other so that both riders move off together.
3 Measure and record the velocities of A and B from just before to just after the collision.
4 Use the velocity data to calculate and record the deceleration of rider A and acceleration of rider B.
5 Calculate the forces *F*(by A on B) and *F*(by B on A).
6 Estimate any uncertainties in the data and their effect on the force calculations.
7 Repeat by launching rider B towards stationary rider A.

DISCUSSION

1 Explain why it is an essential part of the practical activity to jump sideways onto the skateboard.
2 Identify difficulties in producing accurate and precise measurements in these experiments.
3 Suggest ways to improve the quality of the data.

SECTION REVIEW 14.5

REMEMBERING

1 Define the following terms in words and equations.
 a Impulse
 b Momentum
 c Momentum change
2 Write an equation that links impulse and momentum.
3 State what causes the momentum of an object to change.

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4 State the law of conservation of momentum.

UNDERSTANDING

5 Describe the conditions for which the law of conservation of momentum applies.

6 Explain why momentum is conserved at every moment in a collision.

APPLYING

7 The law of conservation of momentum relies on Newton's third law. Explain.

8 a Describe how to use a force–time graph to find impulse and, hence, momentum change.

b Describe how to use an acceleration–time graph to find momentum change and, hence, impulse.

ANALYSING

9 Objects A and B have initial momentums p_{Ai} and p_{Bi}, respectively, along a straight line. They collide, and move off with momentums, p_{Af} and p_{Bf}, respectively. Show that A transfers momentum to B and B transfers momentum to A.

14.6 Solving problems involving collisions

Interactions between objects are frequently referred to as **collisions**. Billiard balls, rugby players and vehicles collide. Any two objects that are subject to mutual forces of interaction in a closed system can be analysed as a collision. In these cases, the conservation of momentum occurs at all times from the start of the collision to its end. Once the mutual forces of the collision have stopped applying, new collisions may occur. For example, a car crash can be considered as an isolated collision during impact. Then, a further collision occurs as the system comes to a stop due to friction between the colliding vehicles and the road.

collision
interaction between two objects subject to action–reaction pairs of forces

Using conservation of momentum to analyse collisions between objects

When using the conservation of momentum to analyse the collisions between objects, complete the following steps:

- Read the question carefully.
- Visualise the situation described; sketches are essential.
- Divide the page into two columns.
- Label the columns 'Before' and 'After'.
- Sketch a diagram in the 'Before' column to show:
  - the situation before the interaction
  - the data provided in the question
  - any missing data.
- Sketch a diagram in the 'After' column to show:
  - the situation after the interaction
  - the data provided in the question
  - any missing data (on the diagram show symbol = ?).

- In the 'Before' column:
  - write an equation for the total momentum before the interaction
  - use symbols for any missing data (on the diagram show symbol = ?)
  - complete any calculations that can be completed.
- In the 'After' column:
  - write an equation for the total momentum after the interaction
  - use symbols for any missing data
  - complete any calculations that can be completed.
- Equate the equations for the 'Before' and 'After' situations, then:
  - solve algebraically
  - substitute numerical values
  - calculate the answer.

WORKED EXAMPLE 14.6.1

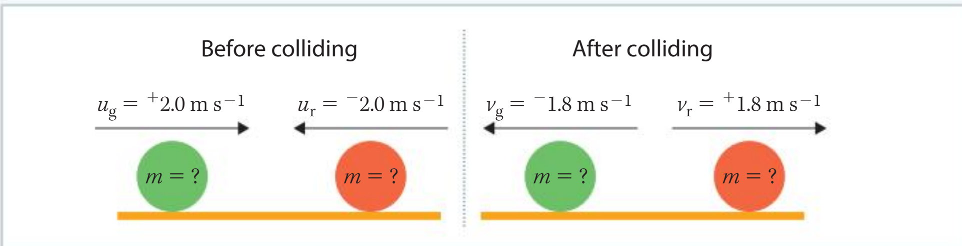
Two billiard balls of equal mass, one green, the other red, move towards each other from opposite directions at 2.0 m s^{-1}. They collide head-on and rebound, both at 1.8 m s^{-1} in directions opposite to their original velocities.

a Sketch the collision in Before and After columns.

b Show how momentum is conserved in this collision.

ANSWERS

a



b In the diagrams, motion to the right has been taken as positive.

$p_{before} = m \times u_g + m \times u_r$

$\Rightarrow p_{before} = m \times {}^{+}2.0\ m\ s^{-1} + m \times {}^{-}2.0\ m\ s^{-1}$

$p_{after} = m \times v_g + m \times v_r$

$\Rightarrow p_{after} = m \times {}^{-}1.8\ m\ s^{-1} + m \times {}^{+}1.8\ m\ s^{-1}$

If conservation of momentum applies, the momentum before the collision should equal the momentum after the collision:

$$p_{before} = p_{after}$$
$$\Rightarrow m \times {}^{+}2.0\ m\ s^{-1} + m \times {}^{-}2.0\ m\ s^{-1} = m \times {}^{-}1.8\ m\ s^{-1} + m \times {}^{+}1.8\ m\ s^{-1}$$
$$\Rightarrow {}^{+}2.0\ m\ s^{-1} + {}^{-}2.0\ m\ s^{-1} = {}^{-}1.8\ m\ s^{-1} + {}^{+}1.8\ m\ s^{-1}$$
$$\Rightarrow 0 = 0$$

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WORKED EXAMPLE (14.6.2)

A 1.5×10^3 kg car is moving to the right at $20\ \text{m s}^{-1}$ while a 5.0×10^3 kg truck is moving to the left at $10\ \text{m s}^{-1}$. The car and truck collide and move off as one mass, stuck together.

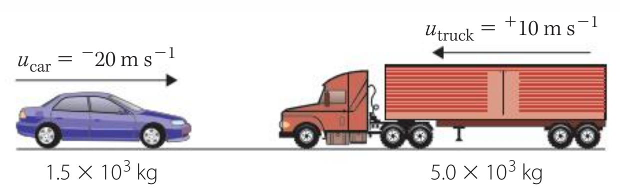
a Draw a diagram showing this situation.

b Calculate the change in the momentum of the truck.

c Find the velocity, v_f, of the wreckage immediately after the collision.

ANSWERS

BEFORE



$$P_{before} = m \times u_{car} + m \times u_{truck}$$
$$\Rightarrow P_{before} = 1.5 \times 10^3\ \text{kg} \times {}^{-}20\ \text{m s}^{-1} + 5.0 \times 10^3\ \text{kg} \times {}^{+}10\ \text{m s}^{-1}$$
$$\Rightarrow P_{before} = 2.0 \times 10^4\ \text{kg m s}^{-1}$$

AFTER

$$P_{after} = (1.5 + 5.0) \times 10^3\ \text{kg} \times v_f$$
$$\Rightarrow P_{after} = 6.5 \times 10^3\ \text{kg} \times v_f$$

$$P_{after} = P_{before}$$
$$\Rightarrow 6.5 \times 10^3\ \text{kg} \times v_f = {}^{+}2.0 \times 10^4\ \text{kg m s}^{-1}$$
$$\Rightarrow v_f = \frac{{}^{+}2.0 \times 10^4\ \text{kg m s}^{-1}}{6.5 \times 10^3\ \text{kg}}$$
$$\Rightarrow v_f = {}^{+}3.1\ \text{m s}^{-1}\ (3.1\ \text{m s}^{-1}, \text{left})$$

Car crashes

Cars are designed to crumple on impact in a collision. This crumpling effect increases the time taken for the crash to be completed. Consequently, the forces applied are, on average, much less than if the cars came to an abrupt stop.

On impact, an unrestrained person inside the car will continue to travel at the original speed, even after the car comes to a stop. This is an example of Newton's first law. Consequently, the person will continue to move towards, and possibly collide with, the windscreen. At $60\ \text{km h}^{-1}$ that has a disastrous effect. This is why seatbelts must be fitted and worn by all occupants in all Australian vehicles. Seatbelts allow the person to come to a stop with the vehicle.

FIGURE 14.6.1 (**a**) Seatbelts in vehicles enable the occupant to come to a stop with the vehicle. (**b**) Unrestrained occupants continue towards the windscreen at the speed of the car when the crash begins. (**c**) A collision with the windscreen can be disastrous.

WORKED EXAMPLE 14.6.3

A 60 kg person is in a car travelling at $90\,\text{km h}^{-1}$ ($25\,\text{m s}^{-1}$) when the car collides with a stationary immovable object and comes to a stop in 0.08 s. The car decelerates at a constant rate because the force applied to the car is constant.

a Find the force applied to the person in the vehicle.

b Explain the advantage of crumple zones by considering what happens to the force on the person when the time over which deceleration occurs is doubled to 0.16 s

ANSWERS

$$J(\text{by car on person}) = \text{change of momentum of occupant}$$

$$\Rightarrow F(\text{by car on person}) \times t = mv - mu$$

a $$\Rightarrow F(\text{by car on person}) = \frac{60\text{ kg} \times 0\text{ m s}^{-1} - 60\text{ kg} \times 25\text{ m s}^{-1}}{0.08\text{ s}}$$

$$\Rightarrow F(\text{by car on person}) = {}^{-}1.9 \times 10^{4}\text{ N}$$

b For a given change of momentum, the equation shows:

$$F(\text{by car on person}) = \frac{mv - mu}{t}$$

$$\Rightarrow F(\text{by car on person}) \propto \frac{1}{t}$$

$$\Rightarrow \text{If } t \times 2\text{, then } F(\text{by car on person}) \times \frac{1}{2}$$

Crumpling increases the time over which a force on the person is applied, so the force is reduced proportionately.

PRACTICAL ACTIVITY 14.6.1

Momentum during a collision

AIM

To analyse the momentum during a collision

MATERIALS

- two dynamics trolley carts
- motion sensor and data logger (or ticker tape timing apparatus)
- spring

Complete a risk analysis by adding to the table.

RISK ANALYSIS

WHAT ARE THE RISKS IN DOING THIS EXPERIMENT?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
The spring may flick back or flick an object into a person's eye.	Wear safety glasses when working with springs.

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PROCEDURE

1 Determine the mass of the two dynamics trolleys carts.
2 Tie the two trolleys together using string with a compressed spring between them, as shown in Figure 14.6.2.
3 Release the trolleys by cutting or burning the string holding them together.
4 Measure and record data so as to find the velocities of each trolley after the 'collision' (the explosion, or cutting of the string). Repeat this three times using the same spring and spring compression.
5 Calculate and record the momentum of the system of the two trolleys before and after each collision.
6 Find the change in the momentum for:
   a each trolley
   b the system.

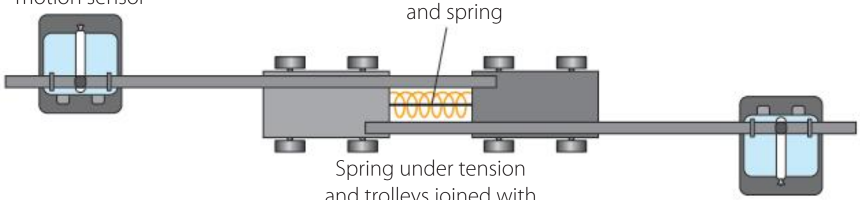

FIGURE 14.6.2 Apparatus for conservation of momentum experiment

RESULTS

1 Record all relevant data collected in order to calculate the speeds of the trolleys.
2 Enter mass, speed and momentum data for each trolley into data tables like the one below.

	MASS OF TROLLEY (kg)	SPEED OF TROLLEY AFTER STRING IS CUT ($m\ s^{-1}$)	MOMENTUM OF TROLLEY ($kg\ m\ s^{-1}$)	CHANGE OF MOMENTUM OF TROLLEY ($kg\ m\ s^{-1}$)
Trial 1				
Trial 2				
Trial 3				
Average				

3 Estimate and record the uncertainty in the average momentum calculations by considering the effect of uncertainties on speed and mass measurements.

REVIEW QUESTIONS

1 Produce a data table that compares both the change of momentum of the two trolleys and the total momentum of the system before and after the collision. Include uncertainties in the table.
2 Decide whether, given the uncertainties in the experiment, the total momentum is conserved in this collision.
3 It is usual to regard a collision in terms of objects hitting each other. Explain how the situation of the trolleys flying apart can also be considered a collision.
4 Discuss improvements to the experimental design that would increase the precision of the measurements.

ANALYSIS OF RESULTS

1 Within the limits of precision, decide whether or not the data confirm:
   a conservation of momentum
   b Newton's third law.

DISCUSSION

1 Identify difficulties in producing accurate and precise measurements in these experiments.
2 Suggest ways to improve the quality of the data.

Interpreting *F*–*t* graphs

A constant force, acting over a time interval is shown in Figure 14.6.3. The impulse of the force during the time interval from t_1 to t_2 is:

KEY FORMULA

$$\vec{J} = \Delta p = \vec{F}t$$

$$\Rightarrow \vec{J} = \vec{F}(t_2 - t_1)$$

$$\Rightarrow \vec{J} = \text{area under } F\text{–}t \text{ graph}$$

Where:

$\vec{J} = \Delta p =$ impulse

$\vec{F}$ = force

t = time interval between instantaneous times t_1 and t_2

Similar to the way in which areas under *s*–*t*, *v*–*t* and *a*–*t* graphs in Chapter 12 were analysed, the area under any *F*–*t* graph can be shown to be the impulse of the force.

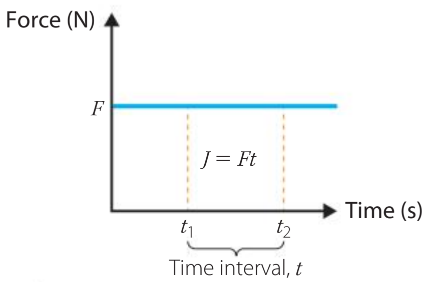

FIGURE 14.6.3 Impulse is the area under the *F*–*t* graph. The area also represents the change of momentum caused by the impulse.

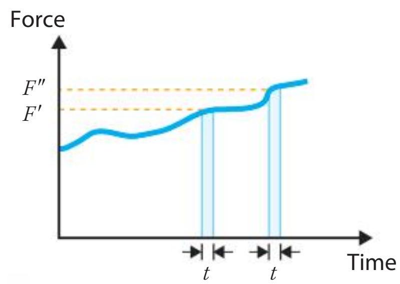

FIGURE 14.6.4 For a force that varies with time, the impulse, hence momentum change, is the area represented by the sum of all the small areas similar to those shown between small time intervals, t: $J = \Sigma(Ft)$.

KEY FORMULA

Impulse = momentum change

= area under *F*–*t* graph

Since the impulse causes the momentum to change, the area also represents the change in momentum.

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WORKED EXAMPLE 14.6.4

Figure 14.6.5 shows the average force applied to a 1000 kg car while braking.

For the first 2.0 s, calculate:

a the impulse of the force applied by the brakes

b the change in momentum of the car

c the change in speed of the car.

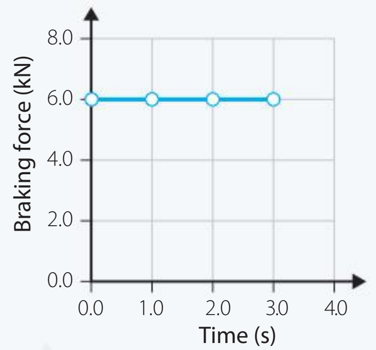

FIGURE 14.6.5

ANSWERS

a Impulse = area under F–t graph

$\Rightarrow J = 6.0 \times 10^3\,\text{N} \times 2.0\,\text{s}$

$\Rightarrow J = 1.2 \times 10^4\,\text{N s}$

b Change of momentum = area under F–t graph

$p_{2.0\,\text{s}} - p_{0\,\text{s}} = 1.2 \times 10^4\,\text{kg m s}^{-1}$

c $p_{2.0\,\text{s}} - p_{0\,\text{s}} = 1.2 \times 10^4\,\text{kg m s}^{-1}$

$\Rightarrow mv_{2.0\,\text{s}} - mv_{0\,\text{s}} = 1.2 \times 10^4\,\text{kg m s}^{-1}$

$\Rightarrow m(v_{2.0\,\text{s}} - v_{0\,\text{s}}) = 1.2 \times 10^4\,\text{kg m s}^{-1}$

$\Rightarrow 1.0 \times 10^3\,\text{kg} \times (v_{2.0\,\text{s}} - v_{0\,\text{s}}) = 1.2 \times 10^4\,\text{kg m s}^{-1}$

$$\Rightarrow v_{2.0\,\text{s}} - v_{0\,\text{s}} = \frac{1.2 \times 10^4\,\text{kg m s}^{-1}}{1.0 \times 10^3\,\text{kg}}$$

$\Rightarrow v_{2.0\,\text{s}} - v_{0\,\text{s}} = 12\,\text{m s}^{-1}$

SECTION REVIEW 14.6

REMEMBERING

1 Summarise the steps needed to solve collision style questions.

UNDERSTANDING

2 In collision problems, explain why it is useful to:

a visualise and sketch the situations described

b set out the answer in Before and After columns.

3 The law of conservation of momentum relies on Newton's third law. Explain.

APPLYING

4 In a crash test, a 1 tonne vehicle travelling at 20 m s^{-1} hits a crash barrier and crumples by 1.0 m in 2.0 s before coming to a stop.

a Calculate the change in momentum.

b Calculate the impulse exerted by the barrier.

c What is the force applied by the car on the barrier?

5 A car travelling at 100 km h^{-1} comes rapidly to a stop. A small, unrestrained dog strikes the windscreen and comes to a stop in 150 ms.

a Use Newton's laws to explain why the unrestrained dog hits the windscreen and comes to a stop.

b Calculate the force applied by the windscreen on the dog.

6 A novice ice skater of mass 50 kg travelling at 3.0 m s^{-1} bumps into a stationary instructor of mass 80 kg. The instructor holds on to the novice so that they move off together. Calculate the speed with which they move off after collision.

ANALYSING

7 Two billiard balls, P and Q, of equal mass move towards each other from opposite directions at 1.5 m s^{-1}. They collide head-on and rebound, both at 0.5 m s^{-1} in directions opposite to their original velocities. Show that the sum of the momentum change of P and Q respectively is zero.

8 Two balls, K and L, move towards each other, collide and rebound. K is travelling in the positive direction initially. Data was recorded and placed in a table.

BALL	MASS (g)	INITIAL SPEED (m s^{-1})	FINAL SPEED (m s^{-1})
K	6.0	5.0	10.0
L	12.0	8.0	0.5

Explain how the data could be, or could not possibly be, correct.

9 A 58 g tennis ball travels at 30 m s^{-1} to the right. It is returned along the same direction. The force applied to the ball rises to a maximum before falling to zero as the ball leaves the racquet (Figure 14.6.6(b)).

a Calculate the impulse of the force on the ball.

b Calculate the change of momentum of the ball.

c Determine the speed of the ball as it leaves the racquet.

a

b

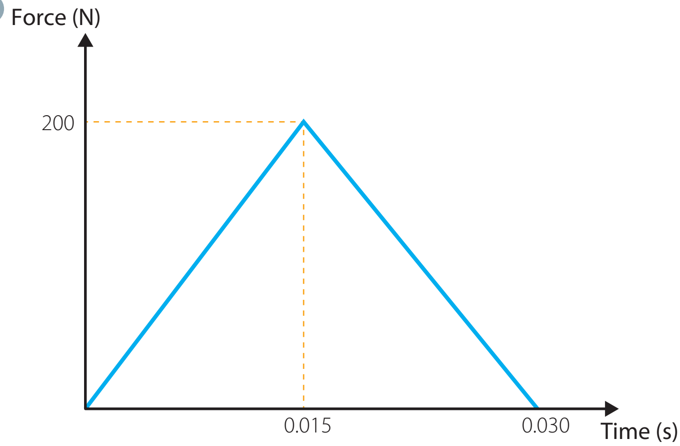

FIGURE 14.6.6

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CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 Identify the criteria that are necessary in order for a pair of forces to be an action–reaction pair. Explain how the idea of force as an external agent is used to develop these criteria.

2 Explain why a constant force does not always produce a constant velocity.

3 Draw a mind map to link mass, acceleration, force, weight, normal, friction, impulse, momentum and Newton's laws.

CATEGORY QUESTIONS

4 Newton's second law is no more than Newton's first law. Discuss.

5 Compare the following terms: force, impulse, momentum.

6 **a** Define 'collision'.

b Give two examples of each of the different types of collisions involving:

i contact forces

ii non-contact forces.

ELABORATION QUESTIONS

7 A teacher puts forward the following argument:

'A gymnast pushes down on the floor to perform a vertical jump. The floor pushes right back with the same force. Since the two forces are equal and opposite they cancel out so the gymnast should not be able to rise above the floor.'

Discuss.

8 A car travelling at relatively low speed is involved in a head-on collision. The car comes to a stop, but a book on the rear window shelf strikes the driver in the back of the head. Explain whether or not the book is thrown forwards during the collision.

EVIDENCE QUESTIONS

9 Tran says that the normal and the weight are an action–reaction pair of forces. Kim says that weight is not a force so Kim must be wrong. Explain whether Tran or Kim is correct. If neither is correct, give correct descriptions of weight and the normal force.

10 During testing cars A and B, travelling at a relatively fast speed, are crashed into a wall and come to a stop on the wall. They both carry identical dummy passengers that are securely restrained by seatbelts. Car A is rigid and has very little damage. Car B crumples significantly on impact. Both dummies experience the same impulse. The dummy passenger in car A is severely damaged but the dummy passenger in car B experiences much less damage.

a Explain why it is important for this scenario that:

i the cars come to a stop on the wall

ii the dummies are securely restrained by seatbelts.

b Explain why the impulse is the same for both dummies.

c Select some reasonable data about mass of dummies, speed of cars and time over which the crashes occur to explain, quantitatively, why the effect on the dummies is so different.

END-OF-CHAPTER EXAM

End-of-chapter test

1 A net force applied to a moving object can cause:

A speed to increase but not decrease.

B velocity to increase but not decrease.

C speed to remain the same but direction to change.

D velocity to remain the same but direction to change.

2 What is the change in momentum of a 50 kg ice-skater who slows from $8.0\,m\,s^{-1}$ to $3.0\,m\,s^{-1}$.

A $^{-}400\,kg\,m\,s^{-1}$

B $^{+}400\,kg\,m\,s^{-1}$

C $^{-}250\,kg\,m\,s^{-1}$

D $^{+}250\,kg\,m\,s^{-1}$

3 For a person standing on a platform, the normal and the weight force:

A are an action–reaction pair of forces.

B add up to a net force of zero.

C are similar types of forces.

D apply to different objects.

4 A person throws a ball directly downwards. While the ball is in flight, what is the action–reaction pair of forces?

A F(by hand on ball); F(by ball on hand)

B F(by hand on ball); weight of ball

C Weight; F(by mass of Earth on ball)

D Weight; F(by ball on mass of Earth)

5 The force that always acts at right angles to a surface is called the:

A weight.

B friction.

C normal force.

D gravitational force.

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6 A 70 kg rower applies a force of 80 N on the water in order to move the boat along a river at $4.0\ m\ s^{-1}$. Which of the following is correct?

A The impulse by the rower and friction are in the same direction.

B The impulse by the rower and friction are in opposite directions.

C The force on the rower and friction are in the same directions.

D The force on the rower and the momentum of the rower are in opposite directions.

7 Complete these sentences:

a Forces are ______________ actions on objects.

b In a collision, the law of conservation of momentum applies at every ______________.

8 Explain how Newton's second law applies for a ball travelling vertically upwards.

9 Identify an appropriate graph from which to find the change of momentum of a particle, and state how to calculate the value using this graph.

10 For two forces to satisfy Newton's third law they must satisfy several criteria. State all of these criteria.

11 Compare mass and weight.

12 A force of 200 N is applied to an object, which accelerates at $4.0\ m\ s^{-2}$. There is a 20 N friction force applied. Find the mass of the object.

13 Find the average net force on an 80 kg athlete who accelerates from rest to $12\ m\ s^{-1}$ in 1.5 s.

14 A 1000 kg car and a 2.00×10^5 kg aeroplane accelerate at the same rate of $3.5\ m\ s^{-2}$. Calculate the ratio of net force on the aeroplane to the net force on the car.

15 Three masses, A (6.0 kg), B (12.0 kg) and C (3.0 kg), are accelerated together along a frictionless horizontal surface by a force of 168 N, as shown in Figure 14.7.1.

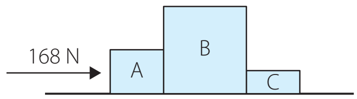

FIGURE 14.7.1

Calculate the magnitude of force exerted by A on B.

16 A baseball travelling horizontally at $32\ m\ s^{-1}$ is in contact with a baseball bat of mass 0.15 kg for 0.75 ms. It returns along the same path at $38\ m\ s^{-1}$.

a Find the change in the momentum of the baseball.

b Calculate the force applied by the ball on the baseball bat.

17 A cricket ball of mass 0.15 kg travels at 35 m s^{-1} horizontally towards the bat. It is struck directly back. The horizontal force applied by the cricket bat on the ball is shown in the Figure 14.7.2. Find the return speed of the ball. Show all working.

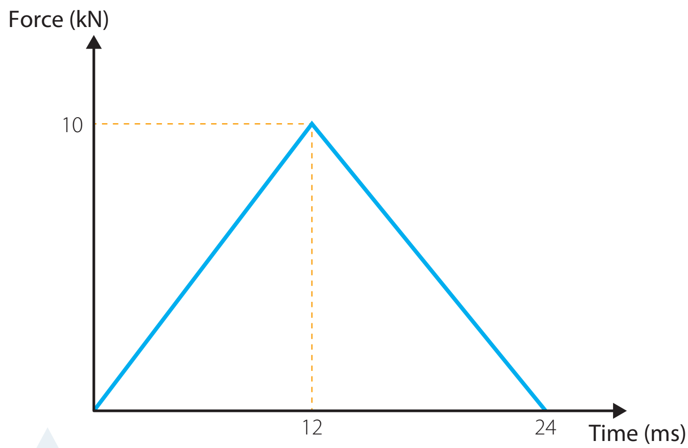

FIGURE 14.7.2

18 Bathroom scales are calibrated on Earth and then taken to the Moon along with a box that weighs 6.0 kg on Earth. Explain how, using the same scales, the box on the Moon appears to have lost 5.0 kg.

19 Discuss whether or not the following statement is true, partially true or false.

'In a car crash, unrestrained occupants are thrown forwards.'

20 Use the concepts of impulse and momentum to explain how crumple zones and seatbelts help reduce injury and death of occupants in cars.

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15 NEWTON'S LAWS OF MOTION

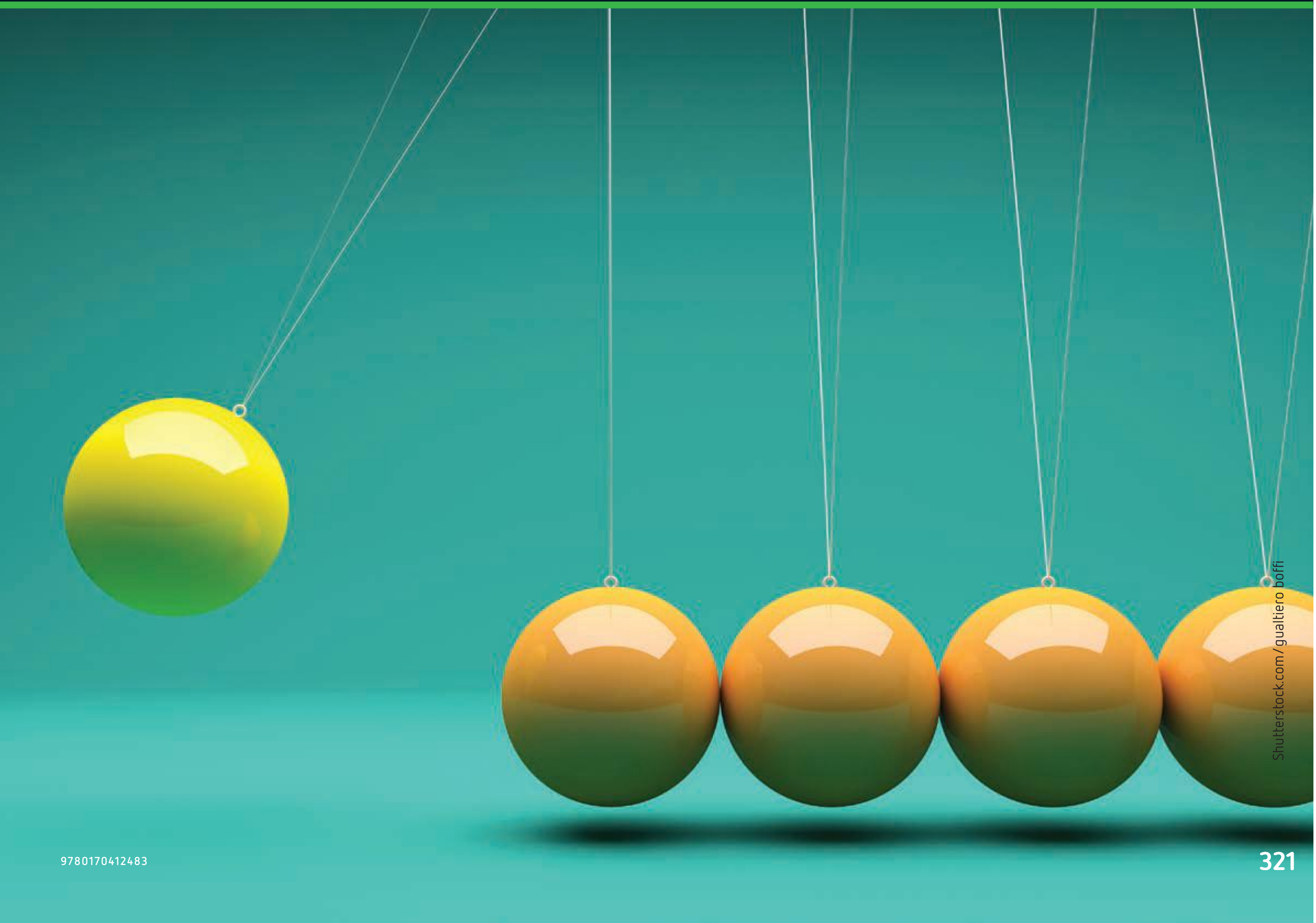
Introduction

In this chapter, attention is turned to the explanation of motion in terms of work and energy. In order to complete a full analysis of motion, we will need to utilise the concepts and related equations of both impulse–momentum and work–energy.

Stimulus questions

All the energy in the universe is still in the universe. No energy has leaked out: where would it go?

All the energy in the universe is still in the universe. No energy has leaked in: where could it come from?



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15.1 Definitions

work
force acting over a distance interval

Displacement and time are the two fundamental measurements of motion. A force acting for a time interval (impulse) causes momentum change. Similarly, a force acting over a distance interval (**work**) causes energy change.

Energy

energy
a fundamental quantity that can be transformed and transferred; it is defined by source or by the way it is measured

Energy is one of the fundamental ideas in physics. According to the Big Bang theory, the universe started as energy. All the energy in the universe is still in the universe. No more energy can be made within the universe. It cannot be made to disappear. Nor can any energy appear from some other universe. The universe is all there is. And the energy in the universe is all the energy there is.

Energy is everywhere, yet it has no clear description. Thermal energy is the kinetic energy associated with particle motion. Atomic and nuclear energy relate to the storage and release of energy from atoms and atomic nuclei. Light energy comes from accelerations of charged particles or atomic energy level transitions. Sound energy is produced by vibrations and measured with a sound meter. Chemical energy is stored between atoms and is released, for example, in foods by metabolic processes. Springs store and release elastic energy. Mass can be converted to and from energy, as Einstein showed in his famous equation: $\Delta E = \Delta mc^2$.

FIGURE 15.1.1 Food is stored chemical energy that is released for use by metabolic processes.

Conservation of energy

isolated system
system that no matter or energy transfers into or out of and in which no energy is created or destroyed

energy change
energy transfer or transformation; quantity of energy that can be measured

The universe is an example of an **isolated system**. In fact, it is the only truly isolated system; inside the universe no energy has been created and none has been destroyed. Energy has, however, been transferred and transformed so that it appears in a great many different locations and forms. Other systems can be made to approximate an isolated system.

Since energy cannot be transferred or transformed, **energy change** is what can be measured. Measurement of change, or difference, in energy from some initial to some final state is represented by the symbol ΔE. ΔE is the difference between two energies or the change in the amount of energy. Note that the symbol ΔE cannot be separated into Δ and E. It is a single symbol, not two symbols multiplied together. The Greek letter delta, Δ, represents 'difference'.

For a system in which energy changes from an initial value E_i to final value E_f, the difference in energy or change in energy is:

$$\Delta E = E_f - E_i$$

KEY FORMULA

$\Delta E = E_f - E_i$

Where:

E_i = initial energy state

E_f = final energy state

Law of conservation of energy

In an isolated system, the energy in the system remains constant and no energy comes in or goes out. Nor is energy created or destroyed in an isolated system. Thus, in an isolated system, the total energy, E_T, remains constant and there is no change of total energy, ΔE_T, in the system.

In an isolated system:

- the total energy, E_T, is constant: E_T = constant
- there is no change of total energy: $\Delta E_T = 0$

KEY FORMULA

Law of conservation of energy

In an isolated system:

E_T = constant and $\Delta E_T = 0$

E_T = total energy

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Work–energy change

When a force acts on an object through a distance, work is done on the object. Work, W, is defined as force multiplied by the distance moved, where the force, $F_{\|}$, and the distance interval, s, are in the same direction; that is parallel to each other:

$$W = F_{\|}s$$

Unit: newton metre = kg m^2 s^{-2} = joule, J

The force and the distance interval must be in the same direction.

When work is done, energy, ΔE, is transferred. This is the work–energy equation:

$$W = \Delta E$$

Energy may be transferred as kinetic energy or potential energy.

KEY FORMULA

$W = F_{\|}s$

Where:

W = work done

$F_{\|}$ = force parallel to the distance interval

s = distance interval parallel to the force

KEY FORMULA

$W = \Delta E$

Where:

W = the work done on the object

ΔE = the change in the energy of the object

Types of energy change

When work is done, energy changes in one of two ways: the **kinetic energy** (energy of movement) of a system can be increased or decreased, or energy may be stored in a system as **potential energy** (energy ready to do work). For example, energy is stored in a spring by applying a force to one or both ends of the spring to compress or stretch it. When the spring is released, the energy can be returned. This will be seen as kinetic energy of, for example, a projectile.

kinetic energy energy of movement

potential energy energy available to do work

15.1.1 Types of energy

15.1.2 Energy forms and changes

Kinetic energy

The work–energy equation can be applied to kinematic equations to produce a quantitative definition of kinetic energy. The kinematic equations for constantly accelerated motion can be used to derive this definition:

$W = F_{\|}s$ (equation 1: work–energy equation)

$F_{\|} = ma$ (equation 2: Newton 2)

$\Rightarrow W = ma \times s$ (equation 1 in equation 2)

$\Rightarrow as = \dfrac{W}{m}$

$\Rightarrow 2as = 2\dfrac{W}{m}$ (equation 3)

$v^2 = u^2 + 2as$ (equation 4: *suvat*)

$\Rightarrow 2as = v^2 - u^2$ (equation 5)

$\Rightarrow 2\dfrac{W}{m} = v^2 - u^2$ (equation 3 in equation 5)

$\Rightarrow \dfrac{W}{m} = \dfrac{1}{2}v^2 - \dfrac{1}{2}u^2$

$\Rightarrow W = \dfrac{1}{2}mv^2 - \dfrac{1}{2}mu^2$

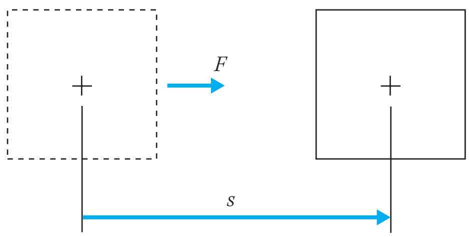

FIGURE 15.1.2 Work is done on an object by a force that is parallel to the direction of the distance interval, s.

This equation shows that the work has changed the value of the quantity ½ × (mass) × (speed)^2. This generalised quantity is called kinetic energy, E_k:

$$E_k = \frac{1}{2}mv^2$$

KEY FORMULA

$E_k = \dfrac{1}{2}mv^2$

Where:

E_k = kinetic energy

m = mass

v = speed

PRACTICAL ACTIVITY 15.1.1

Force applied in a model car crash

When a vehicle crashes into a solid wall, it loses kinetic energy. The vehicle also crumples. The change of kinetic energy and the crumple distance can be used to find the force applied to the car by the wall. In this experiment, the speed of a trolley is used to find its kinetic energy. The work done on the trolley by the wall, W, causes the kinetic energy to be reduced to zero. W is related to the force applied by the wall, F(by wall on trolley), and the crumple distance, s:

$$W = Fs = \Delta E_k$$

$$\Rightarrow Fs = \frac{1}{2}mv^2$$

$$\Rightarrow F = \frac{\frac{1}{2}mv^2}{s}$$

AIMS

The aims of this experiment are:

- to simulate a car crash
- to compare the forces applied when the crash occurs at different energies.

MATERIALS

- data logger or motion-sensing app
- dynamics trolley or toy car
- weighing machine
- plasticine
- ruler
- long plank, minimum 2 m
- solid wall

PROCEDURE

- Set up the plank near the wall as shown.

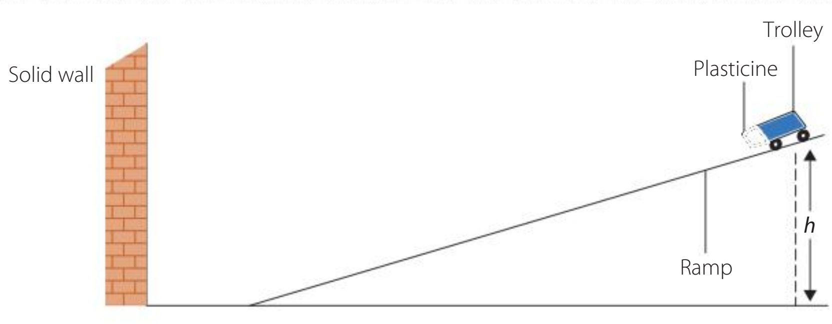

FIGURE 15.1.3 Experimental set-up

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Trial run

1 Set up the data logger to measure the speed of the trolley as close as possible to the wall.
2 Attach plasticine to the front of the trolley.
3 Roll the trolley from the highest point.
4 Observe the crash.
   a If the trolley bounces back, add more plasticine and repeat until the trolley does not bounce back.
   b If it is difficult to measure the crumple distance, gently heat the plasticine so it can deform more readily.
5 Make sure the speed can be measured consistently.

Data collection

1 Weigh the trolley and record its mass.
2 Roll the trolley from at least five different heights.
3 Measure the amount the plasticine crumples.
4 Record the data in a data table like the one below.

RUN NUMBER	RELEASE HEIGHT, h ± uncertainty (cm)	SPEED AT WALL, v ± uncertainty ($cm\,s^{-1}$)	CRUMPLE DISTANCE, s ± uncertainty (mm)

RESULTS

1 Plot the graph of speed, v, versus release height, h.
   Use the graph to determine any relationship between v and h.
2 Construct a data table showing the speed and kinetic energy, E_k, at the wall, as well as the crumple distance and the force applied by the wall. Include uncertainties in each value.
3 Plot the graph of crumple distance, s, versus kinetic energy, change, ΔE_k.

REVIEW QUESTIONS

1 Explain whether the height of release, h, can be used as a measure of the kinetic energy, E_k, at the wall.
2 Discuss what would happen to the force in this experiment if the speed was kept constant but the plasticine was made firmer or softer.
3 Discuss how this practical activity could be used to understand car design.

CONCLUSION

1 Report the main findings.
2 Describe limitations to the validity and reliability of the raw and derived data.
3 Indicate what might be done better to show the relationship between the kinetic energy of the trolley and the crumple distance.

Potential energy

elastic potential energy
energy stored in a spring system

gravitational potential energy
energy stored in a system comprising masses subject to gravitational force

Energy may also be added to or removed from a system without the system gaining or losing kinetic energy. In these cases, the energy is stored in the system as potential energy. Potential energy is not associated with a particular object but with the system in which the object is found. For example, energy from an external source can be stored as potential energy in a spring by stretching or compressing the spring. The spring system can return this **elastic potential energy** as kinetic energy when released.

Similarly, when energy is used to lift a mass up against the gravitational force, the energy is stored in the system of the two masses (Earth and object). When the object is released, this **gravitational potential energy** stored in the system can be returned as kinetic energy. This kinetic energy is usually observed as kinetic energy of a mass. But it is actually the kinetic energy of the system that has increased at the expense of the potential energy that has decreased. The total of potential energy and kinetic energy remains constant.

SECTION REVIEW 15.1

REMEMBERING

1 Define 'energy', 'energy change', 'work', 'kinetic energy', 'potential energy', 'elastic potential energy' and 'gravitational potential energy'.

2 Recall the law of conservation of energy.

UNDERSTANDING

3 The law of conservation of energy only applies to isolated systems. Explain.

4 **a** Write the work–energy equation in words and symbols.

b Define each term in the equation.

5 Explain why it is only possible to measure changes of energy.

6 Use examples from two different forms of energy to explain how potential energy is stored.

APPLYING

7 Calculate the kinetic energy of a 3.0 kg mass that is travelling at the following speeds.

a $8.0\,\text{m}\,\text{s}^{-1}$

b $60\,\text{km}\,\text{h}^{-1}$

8 A force of 20 N is applied over a distance of 5.0 m to an 8.0 kg object travelling at $10\,\text{m}\,\text{s}^{-1}$. The force and the distance are in the same direction.

a Calculate the change in kinetic energy of the object.

b Determine the final speed of the object.

ANALYSING

9 A force is continuously applied to a moving object at right angles to the motion of the object. This causes the object to change direction.

a Describe the motion of the object.

b Explain why no work is done on the object by the force.

REFLECTING

10 Connect the ideas and formulas about work and energy in a mind map.

15.2 Solving problems: work done by forces

Work may be done by forces that are constant, uniformly increasing or decreasing or that vary continuously in an irregular way. Force–distance graphs can be used to assist in the determination of work done. In all these graphs, the force that is doing the work is parallel to the distance.

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Work done by a constant force

Figure 15.2.1 shows a constant force, F(by A on B), acting to move object B over a distance interval, s. The work done on B is:

$$W(\text{by A on B}) = F(\text{by A on B}) \times s = \text{area under } F\text{–}s \text{ graph}$$

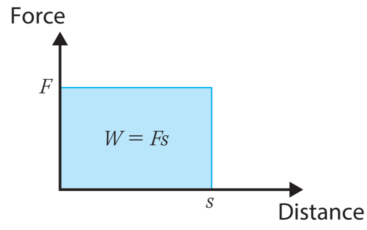

FIGURE 15.2.1 Work done is the area under the F–s graph.

Work done by the component of a force parallel to the direction of motion

Some forces are applied at an angle to the direction of motion. For example, a suitcase is pulled horizontally while the person is applying a force that is somewhat directed upwards. A lawnmower or vacuum cleaner is pushed in a downwards direction while moving horizontally. In these cases, it is only the component of the force parallel to the direction of motion that does work.

If the force is directed at an angle, θ, to the distance travelled, then the component of the force, $F_{\parallel}$, is:

$$F_{\parallel} = F\cos\theta$$

Thus, the work done is:

$$W = F_{\parallel}s = Fs\cos\theta$$

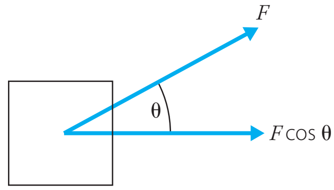

FIGURE 15.2.2 Only the component of a force parallel to the distance travelled does work: $F_{\parallel} = F\cos\theta$.

KEY FORMULA

$W = F_{\parallel}s = Fs\cos\theta$

Where:

W = work done on an object

F = force applied on the object parallel to the direction of the distance travelled

s = distance travelled by the object

θ = angle between the force and the direction of the distance travelled

Work done by a stepwise force

If the force by A on B changes from one constant force to another constant force, then the total work done is the sum of the areas under each section of an F–s graph, as shown in Figure 15.2.3.

$$W(\text{on B}) = \text{area under } F\text{–}s \text{ graph}$$

$$W(\text{on B}) = \sum\{F(\text{by A on B}) \times s\}$$

$$W(\text{on B}) = \{F_1(\text{by A on B}) \times s_1\} + \{F_2(\text{by B on A}) \times (s_2 - s_1)\}$$

Any force that varies with distance

The area under any F–s graph is the work done, and hence the energy transferred, by the force. The work, W', done by a force, F', over a small distance interval, s', is $W' = F's'$. Similarly, the work, W'', done in distance interval s'' by force F'' is $F''s''$.

The total work done, then, is the sum of all the W'. Hence:

$$W = \sum(F's')$$

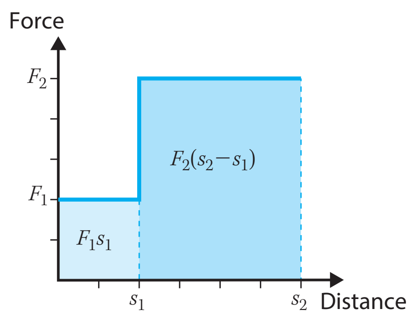

FIGURE 15.2.3 Work done by forces on B is the sum of all the areas under the F–s graph.

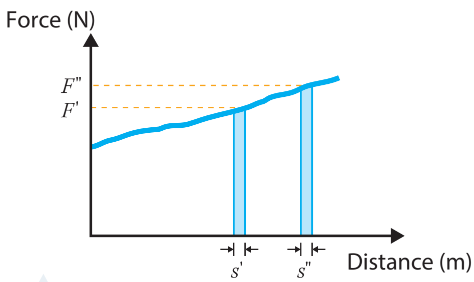

FIGURE 15.2.4 Work done is the sum of all the small areas similar to $F's'$ and $F''s''$. The area is also the energy transfer to or from a system.

Work done by a constantly increasing force

Spring-like forces form a very significant group. They apply for everyday springs as well as large-scale building materials. The force applied by a spring is a function of the spring system. By Newton's third law, the force applied by a spring is equal to the force applied to a spring. When a force is applied to a spring to cause it to change length, then the spring system applies the same magnitude of force but in the opposite direction. The change in length is, therefore, always in the opposite direction to the force applied by the spring. The spring applies a restoring force. For a significant group of elastic materials, the restoring force applied by the spring is proportional to the change of length of the spring, This is known as Hooke's law:

$$F(\text{by spring}) \propto {}^{-}x$$

$$\Rightarrow F(\text{by spring}) = k({}^{-}x)$$

KEY FORMULA

Hooke's law

$F(\text{by spring}) \propto {}^{-}x$

$\Rightarrow F(\text{by spring}) = k({}^{-}x)$

Where:

F(by spring) = force applied by a spring to an external cause

x = change of length of spring

k = constant of proportionality = stiffness

Hooke's law refers to a property of the spring. That is, it relates to the force applied by the spring, not the force applied on the spring.

The constant of proportionality, k, has physical meaning. It is the stiffness of the spring. The larger the value of k, the stiffer the spring.

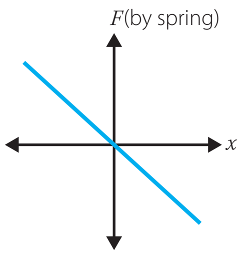

FIGURE 15.2.5 Hooke's law: the force by the spring and the extension are oppositely directed.

Potential energy stored in spring systems

In most cases, the analysis of springs involves the potential energy stored in the spring. The energy stored in the spring comes from the work done on the spring by an external force. By Newton's third law, the force applied by the spring to store the energy is equal in magnitude to the external force applied on the spring.

For springs that obey Hooke's law, it is usual to draw F–x graphs in the first quadrant, where the force axis actually represents the magnitude of the force applied by the spring: F(by spring). The force applied on the spring, F(on spring), is responsible for the extension of the spring, x. This means that the extension is dependent on the force (independent variable) applied on the spring and the graph should be an x–F(on spring) graph. However, it is the extension that causes the spring to apply a force, so the graph should be F(by spring)–x. The F(by spring)–x graph looks like Figure 15.2.5 because F(by spring) and the extension, x, that causes it are in opposite directions.

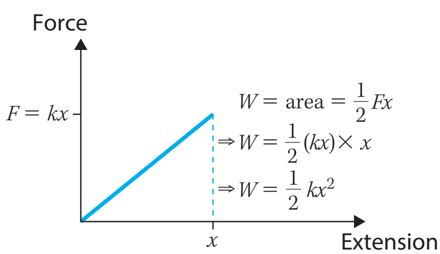

FIGURE 15.2.6 The magnitude of the force applied by the spring is a function of the magnitude of the extension that causes this force.

The usual presentation of Hooke's law is shown in Figure 15.2.6. The graph is simplified by graphing the magnitude of the force applied by the spring against the extension that caused it: F(by spring)–x.

The potential energy taken up by the spring system is the area under the F–x graph:

$$W = \text{area} = \frac{1}{2}Fx$$

$$\Rightarrow W = \frac{1}{2}(kx) \times x$$

$$\Rightarrow W = \frac{1}{2}kx^2$$

KEY FORMULA

$W = \frac{1}{2}kx^2$

Where:

W = potential energy stored in a spring, J

k = stiffness, N m^{-1}

x = extension (or compression) of the spring, m

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INQUIRING FURTHER

Helical springs are used in suspension systems of small cars, motorcycles and bicycles. Leaf springs are used in larger vehicles and trucks. In the aerospace industries, coiled springs are used in switches and levers. Springs are also used widely in the oil and gas industries. In telecommunications, flat springs and pressings are used for keypads. Create a visual report of the use of springs in industry, transport and telecommunications.

PRACTICAL ACTIVITY 15.2.1

Potential energy in springs

Extension and compression can be used to measure the stiffness of, and the potential energy stored in, a spring. When a spring is extended, it is said to be 'in tension'. When it is compressed, it is 'in compression'. Both forces are 'restorative forces' because they have the direction that would restore the spring to its original length.

The purpose of this practical activity is to find the following for a variety of springs:

- the stiffness
- the potential energy in the spring system.

MATERIALS

- 3 open springs that can be compressed and extended
- force measurer: a data logger or mechanical spring balance
- ruler
- clamp

PROCEDURE

1 Complete the data table to include all risks and their management.

WHAT ARE THE RISKS IN DOING THIS EXPERIMENT?	HOW CAN YOU MANAGE THESE RISKS TO STAY SAFE?
The spring may flick back or flick an object into a person's eye.	Wear safety glasses when working with springs.

RISK ASSESSMENT

2 Measure extension as a function of force applied for each spring. The maximum extension should be the same for each spring.

3 For each spring in tension, construct a data table that includes the following data.

SPRING	EXTENSION OF SPRING, x (m)	UNCERTAINTY IN EXTENSION (m)	FORCE APPLIED BY SPRING, F(by spring) (N)	UNCERTAINTY IN F(by spring) (N)

4 Repeat steps 2 and 3 for the springs in compression.

»

RESULTS

1 For each spring under both tension and compression:

   a plot a graph of F(by spring) versus x, including uncertainty bars (Do not assume the line includes the origin.)

   b find the value of the stiffness, k, for each spring (gradient)

   c find the amount of potential energy stored in the spring, E_P.

2 Report these derived data in a properly constructed data table.

DISCUSSION

1 For each spring, compare the stiffness under extension with the stiffness under compression.

2 Compare the springs in both tension and compression with respect to:

   a stiffness

   b maximum potential energy measured.

3 Explain why the comparisons of stiffness and stored energy rely on the springs being the same length *and* the same diameter.

4 Explain why the graph line may not include (0, 0).

CONCLUSION

1 Report the main findings in a data table.

2 Describe limitations to the validity and reliability of the raw and derived data.

3 Indicate what might be done better to make fair comparisons between springs.

SECTION REVIEW 15.2

REMEMBERING

1 Define 'work' in words and symbols.

2 Describe the relationship between work and energy.

3 Given a force–distance graph, recall how to calculate the work done.

UNDERSTANDING

4 Use a diagram to help define the work done by a force that is acting at an angle to the direction of motion. On the diagram, show the definition of each symbol used.

5 Consider springs that obey Hooke's law.

   a Write Hooke's law in symbols.

   b Define each symbol used.

   c On an appropriate graph show:

      i stiffness

      ii energy stored in the spring.

APPLYING

6 In a test crash, a force of 1.5×10^5 N is applied over 5.0 cm to a dummy head form. Find the work done on the head form.

7 A force of 30 N is applied at an angle of 30° to the horizontal on a box in order to drag the box 20 m across a horizontal surface. Calculate the work done by the force on the box.

8 A winch applies a 400 N force to pull a 250 kg boat across a 15 m long horizontal surface. For the last 6.0 m a second winch is attached to assist. It applies an additional force of 200 N. Calculate the combined work done by the winches in order to pull the boat across the surface.

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ANALYSING

9 A 30 cm length of spring obeys Hooke's law. It has a stiffness of 50 N m^{-1}. It can be extended to a maximum length of 50 cm.

a Draw a graph to show how the spring extension and force applied by the spring are related. Provide numerical values for the axes.

b Calculate the energy stored in the spring when it is 50 cm long.

15.3 Solving problems: kinetic energy and gravitational potential energy

Near Earth's surface a constant force, $F = mg$, is applied to each mass. When a mass, m, falls from a position above Earth towards Earth, the gravitational force, mg, is applied over a distance Δh, which increases as the ball falls. This force does work, W, on the mass. The greater the distance of the fall, the greater the work done. All of this work transfers an amount of kinetic energy, ΔE_k, so that the mass moves at increasing speed from initial speed, u, to final speed, v. The gravitational force applied on the mass works to impart a change in the kinetic energy of the system. This change is all associated with the mass, as long as air resistance is regarded as negligible. Work and gain in kinetic energy are equivalent:

$$W = \Delta E_k$$

$$\Rightarrow mg\Delta h = \Delta E_k$$

$$\Rightarrow mg\Delta h = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$$

It is important to consider the mass before it began to descend. If the mass is to gain kinetic energy, the energy needs to be available in the first place. In order to be at its position, the mass must have been lifted up against the gravitational force. The energy need to lift the mass by a distance, Δh, is the work done to raise it by this amount.

This is equal to the energy added into the system as potential energy, ΔE_p:

$$W = \Delta E_p$$

$$\Rightarrow \Delta E_p = mg \times \Delta h$$

The change of total energy, ΔE_T in this system is zero:

$$\Delta E_T = \Delta E_k + \Delta E_p = 0$$

$$\Rightarrow \Delta E_k = {}^{-}\Delta E_p$$

Since the total change in energy in the system is zero, the positive gain in kinetic energy as the mass falls is provided by a consequent negative gain (a loss) in potential energy of the system. Similarly, as a mass rises against the gravitational force, the negative change in kinetic energy is transformed into a positive gain in potential energy of the system: ${}^{-}\Delta E_k = {}^{+}\Delta E_p$. Whether the mass is rising or falling, the total change in energy of the system is zero.

KEY FORMULA

$$\Delta E_k = mg\Delta h$$

$$\Rightarrow mg\Delta h = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$$

Where:

Δh = distance travelled

v = final speed

u = initial speed

KEY FORMULA

$$W = \Delta E_p$$

$$\Rightarrow \Delta E_p = mg \times \Delta h$$

KEY FORMULA

Near Earth, where air resistance is negligible:

$${}^{+}\Delta E_k = {}^{-}\Delta E_p$$

Where:

ΔE_k = change in kinetic energy

ΔE_p = change in potential energy

'+' sign means 'gain'; the '–' sign means 'loss'

KEY FORMULA

$$\Delta E_k + \Delta E_p = 0$$

$$\Rightarrow {}^{+}\Delta E_k = {}^{-}\Delta E_p \quad \text{(falling mass)}$$

$$\Rightarrow {}^{-}\Delta E_k = {}^{+}\Delta E_p \quad \text{(rising mass)}$$

Where:

ΔE_k = change in kinetic energy

ΔE_p = change in potential energy

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Zero of gravitational potential energy

For objects that move vertically near Earth, it is useful to define a position where the gravitational potential energy of the Earth–mass system is zero. This is usually taken as the point of projection. The potential energy of the system then increases as the height above the zero point increases. Consequently, there is an equal decrease in kinetic energy of the system that is usually associated with the projectile. This coincides with experience. A ball thrown up at speed v_{max} loses speed, hence kinetic energy. It momentarily stops at the top of its flight, h_{max}. On the way down, the speed, hence the kinetic energy, increases until all the potential energy has been expended back at the zero point. At the top point, the kinetic energy at launch has all been converted to potential energy. The two values are equal:

$$mgh_{max} = \frac{1}{2}mv^2_{max}$$

- The maximum launch speed can be deduced by measuring the maximum height above the zero of potential energy:

$$v_{max} = \sqrt{2gh_{max}}$$

- The maximum height can be deduced by measuring the launch speed at the zero of potential energy:

$$h_{max} = \frac{v^2_{max}}{2g}$$

KEY FORMULA

For vertical projection from $h = 0$:

$$mgh_{max} = \frac{1}{2}mv^2_{max}$$

$$v_{max} = \sqrt{2gh_{max}} \quad \text{or} \quad h_{max} = \frac{v^2_{max}}{2g}$$

Where:

v_{max} = maximum speed at launch

h_{max} = maximum height reached above zero of potential energy

v_{max} = maximum launch speed

m = mass

g = acceleration due to gravity

Solving problems involving vertical displacements

To solve problems in which objects move vertically near Earth, a work–energy analysis is usually useful.

For changes in potential energy, $\Delta E_p = mg\Delta h = mg(h_f - h_i)$.

- Identify the initial height, h_i.
- Identify the final height, h_f.
- Substitute values into the equation.
- Calculate the answer.

For changes in kinetic energy:

$$\Delta E_k = \frac{1}{2}mv_f^{\,2} - \frac{1}{2}mv_i^{\,2} = \frac{1}{2}m\left(v_f^{\,2} - v_i^{\,2}\right)$$

- Identify the initial speed, v_i.
- Identify the final speed, v_f.
- Substitute values into the equation.
- Calculate the answer.

It is frequently necessary to equate kinetic energy changes with potential energy changes in order to find height changes or speed changes. If measurements are made relative to the zero of potential energy, then:

- at the bottom of the flight, $h_i = 0$ and $E_p = 0$.
- at the top of the flight, $v_f = 0$ and $E_k = 0$.

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In these cases, substitute values into either:

$$v_{max} = \sqrt{2gh_{max}} \quad \text{or} \quad h_{max} = \frac{v^2_{max}}{2g}$$

WORKED EXAMPLE 15.3.1

A rhythmic gymnast throws a 420 g ball vertically upwards to a height of 8.0 m.

a Calculate the potential energy gain at the top of the ball's flight.

b Determine the speed of the ball as it leaves the gymnast's hand.

ANSWERS

a $\Delta E_p = mg\Delta h$

$\Rightarrow \Delta E_p = 0.42\,\text{kg} \times 9.8\,\text{m s}^{-2} \times (8.0\,\text{m} - 0\,\text{m})$

$\Rightarrow \Delta E_p = 33\,\text{J}$

b $\Delta E_k = -\Delta E_p$

$\Rightarrow \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2 = -33\,\text{J}$

$\Rightarrow \frac{1}{2}m(0)^2 - \frac{1}{2}mv_i^2 = -33\,\text{J}$

$\Rightarrow \frac{1}{2}mv_i^2 = 33\,\text{J}$

$\Rightarrow v_i = \sqrt{\frac{2 \times 33\,\text{J}}{0.42\,\text{kg}}}$

$\Rightarrow v_i = 13\,\text{m s}^{-1}\,(12.5\,\text{m s}^{-1})$

When objects move at right angles to Earth's gravitational force, there is no gravitational force component in the direction of motion, therefore no work is done by the gravitational force. Thus, a body that is simultaneously moving vertically and horizontally, such as a ball thrown from one person to another, is only worked on by the gravitational force as it moves vertically up or down but not as it moves sideways.

WORKED EXAMPLE 15.3.2

A waterslide starts from a height of 15 m above the ground. A 40 kg person sits at the top of the waterslide.

a Calculate the potential energy associated with the person at the top of the slide.

b Find the maximum kinetic energy the person will gain when sliding to the bottom of the slide.

c Calculate the maximum speed of the person.

d Will a 60 kg person go down the slide faster than the 40 kg person? Give reasons for your answer.

ANSWERS

a $E_p = mg\Delta h$

$\Rightarrow E_p = 40\,\text{kg} \times 9.8\,\text{m s}^{-2} \times (15\,\text{m} - 0\,\text{m})$

$\Rightarrow E_p = 5.9 \times 10^3\,\text{J}$

b $^{+}\Delta E_k = {}^{-}\Delta E_p$

$^{+}\Delta E_k = {}^{-}[40\,\text{kg} \times 9.8\,\text{m}\,\text{s}^{-2} \times (0\,\text{m} - 15\,\text{m})]$

$^{+}\Delta E_k = 5.9 \times 10^3\,\text{J}$

c $\Delta E_k = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$

$\Rightarrow \Delta E_k = \frac{1}{2}mv^2 - 0$

$\Rightarrow v = \sqrt{\frac{2\Delta E_k}{m}}$

$\Rightarrow v = \sqrt{\frac{2 \times 5.9 \times 10^3\,\text{J}}{40\,\text{kg}}}$

$\Rightarrow v = 17\,\text{m}\,\text{s}^{-1}$

d No. The speed at the bottom will be the same, no matter the mass (so long as friction is negligible).

$v = \sqrt{\frac{2\Delta E_k}{m}}$

$\Rightarrow v = \sqrt{\frac{2 \times mg\Delta h}{m}}$

$\Rightarrow v = \sqrt{2g\Delta h}$

This is independent of the mass.

SECTION REVIEW 15.3

REMEMBERING

1 Write the equation that connects *change* in total energy, *change* in kinetic energy and *change* in potential energy.

2 Write the equation that connects work done by Earth's gravitational force on a mass that:

a is lifted by a distance Δh

b falls by a distance Δh.

3 A mass, m, is projected upwards with an initial speed v_i, and reaches a maximum height, H, above the ground. Write the equation that:

a links the maximum kinetic energy with the maximum potential energy in the Earth–mass system

b enables calculation of v_i from measurements of H

c enables calculation of H from measurements of v_i.

UNDERSTANDING

4 For masses 'near Earth', it is usual to define the zero of potential energy at Earth's surface. Explain why this is useful.

5 Explain why gravitational potential energy is only transferred when a mass moves vertically but not horizontally.

APPLYING

6 A cricketer throws a 160 g ball vertically upwards to a height of 20.0 m.

a Calculate the potential energy gain at the top of the ball's flight.

b Determine the speed of the ball as it leaves the cricketer's hand.

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7 A 50 kg person slips down a fun park slide that is 20 m high. Calculate the changes in potential energy and kinetic energy of the system at:

a the top of the slide

b the bottom of the slide

c halfway down the slide.

ANALYSING

8 A 2.0 kg projectile is launched from the ground vertically upwards at $20\ \mathrm{m\ s^{-1}}$. Use calculations to show that it does not matter whether the initial potential energy of the system is zero or 100 J at Earth's surface.

15.4 Interpreting graphs

Graphs are frequently drawn to show aspects of motion. A force–time graph relates to an analysis of impulse–momentum. Force–distance graphs are used for work–energy analyses. For movement that is subject to the gravitational force near Earth, the force–distance graph shows a constant force as distance changes. Frequently, force–extension graphs are drawn for springs. In both these cases, the area under the force–distance graph is the work done, hence energy change, in the system.

Solve problems involving force–distance graphs by the following steps.

- Read the question carefully.
- Visualise the situation.
- Check the scales on both axes.
- Convert all scale readings to appropriate SI units.
- Identify the area required as:
  - work done on or by the system.
  - kinetic energy increase or decrease.
  - potential energy increase or decrease.
- Set up appropriate equations.
- Equate energy changes with areas.
- Substitute values.
- Calculate the answers.
- Check to ensure the results answer the question.

WORKED EXAMPLE 15.4.1

Figure 15.4.1 shows the force applied by one and then two people pulling a 50 kg box, initially at rest, over a frictionless floor.

a Calculate the work done by:

i the first person before the second person started to pull

ii the second person assuming the first person continues to pull with the same force as before.

b Calculate the kinetic energy gained by the box after it has been pulled 12 m.

c Calculate the speed of the box at 12 m.

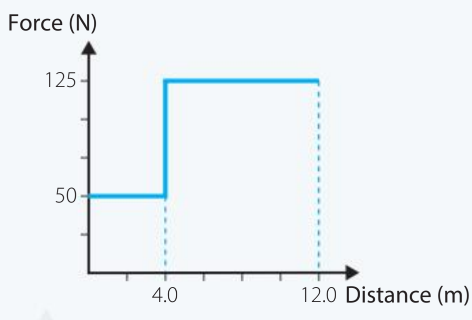

FIGURE 15.4.1

ANSWERS

a **i** W = area under graph

$\Rightarrow W = 50\,\text{N} \times 4.0\,\text{m}$

$\Rightarrow W = 200\,\text{J}$

ii W = area under graph

$\Rightarrow W = (125\,\text{N} - 50\,\text{N}) \times (12.0\,\text{m} - 4.0\,\text{m})$

$\Rightarrow W = 75\,\text{N} \times 8.0\,\text{m}$

$\Rightarrow W = 600\,\text{J}$

b W = area under graph

$\Rightarrow W = (50\,\text{N} \times 12.0\,\text{m}) + 600\,\text{J}$

$\Rightarrow W = 1.2 \times 10^3\,\text{J}$

c $W = \Delta E_k$

$$W = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$$

$$\Rightarrow \frac{1}{2}mv^2 = 1200\text{ J}\left(u = 0\text{ m s}^{-1}\right)$$

$$\Rightarrow v = \sqrt{\frac{2 \times 1200\text{ J}}{50\text{ kg}}}$$

$$\Rightarrow v = 6.9\text{ m s}^{-1}$$

WORKED EXAMPLE 15.4.2

Figure 15.4.2 shows the magnitude of a force applied by a spring as a function of the compression of the spring.
A 40.0 g ball bearing is placed at the end of the spring ready to be launched horizontally.

a Calculate the stiffness of the spring.

b Find the energy stored in the spring when it is compressed by 40 cm.

c Calculate the speed of the ball bearing when the spring is released from a compression of 40 cm.

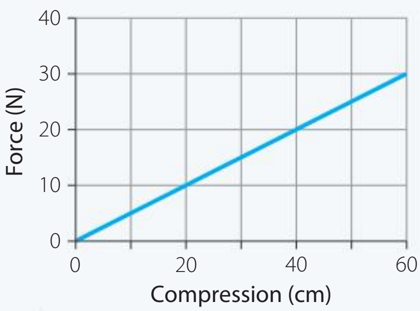

FIGURE 15.4.2

ANSWERS

a Note that the x axis scale is in centimetres, therefore convert to metres:
k = gradient of F–x graph

$$\Rightarrow k = \frac{30\text{ N}}{0.60\text{ m}}$$

$$\Rightarrow k = 50\text{ N m}^{-1}$$

b ΔE_p = area under F–x graph

$$\Delta E_p = \frac{1}{2} \times 20\text{ N} \times 0.40\text{ m}$$

$$\Rightarrow \Delta E_p = 4.0\text{ J}$$

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c Note that the mass is in grams; therefore, convert to kilograms.

$$\Delta E_k = \Delta E_p$$
$$\Rightarrow \Delta E_k = 4.0\ \text{J}$$
$$\Rightarrow \Delta E_k = \frac{1}{2}m\left(v_f^2 - v_i^2\right) = 4.0\ \text{J}$$
$$\Rightarrow \frac{1}{2}m\left(v_f^2 - v_i^2\right) = 4.0\ \text{J}$$
$$\Rightarrow \frac{1}{2}\times 4.0\times 10^{-2}\ \text{kg}\times\left[v_f^2 - \left(0\ \text{m s}^{-1}\right)^2\right] = 4.0\ \text{J}$$
$$\Rightarrow 2.0\times 10^{-2}\ \text{kg}\times v_f^2 = 4.0\ \text{J}$$
$$\Rightarrow v_f = \sqrt{\frac{4.0\ \text{J}}{2.0\times 10^{-2}\ \text{kg}}}$$
$$\Rightarrow v_f = 14\ \text{m s}^{-1}$$

SECTION REVIEW 15.4

REMEMBERING

1 Write down the steps needed in order to solve problems involving force–distance graphs.

UNDERSTANDING

2 Explain why the area under a force–distance graph can be used to measure energy change.

3 Show that the energy stored in a spring that obeys Hooke's law, $F = k(^-x)$, is $\frac{1}{2}kx^2$, when the spring is extended by an amount x.

APPLYING

4 The force–distance graph (Figure 15.4.3) is shown for a particle of mass 1.5 kg.

Calculate the work done:

a in the first 10 m

b between 3.0 m and 17 m.

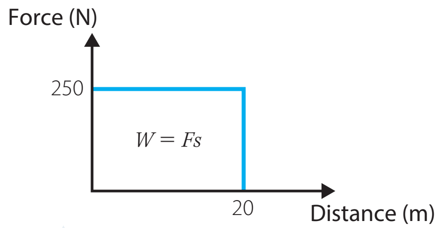

FIGURE 15.4.3

5 Person A pulls a heavy load across a floor. Later, person B comes to assist. The friction force is a constant 28 N (Figure 15.4.4).

a Calculate the work done by person A after the load has travelled:

i 4.0 m

ii 16 m.

b Calculate the work done by person B after the load has travelled:

i 12 m

ii 20 m.

c Calculate the work done by the friction force after 24 m.

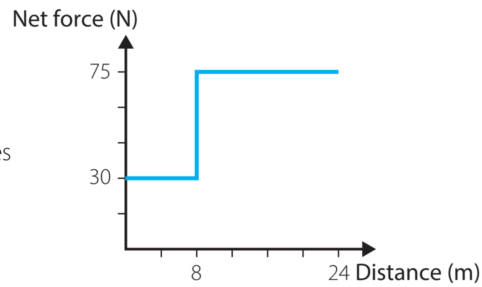

FIGURE 15.4.4

6 The speed–time graph for a goods train is shown in Figure 15.4.5. The mass of the train is 5500 tonne. The total frictional forces on the train are 1.0×10^4 N.

Calculate the work done by the train:

a in the first 600 s

b between 1200 s and 1800 s.

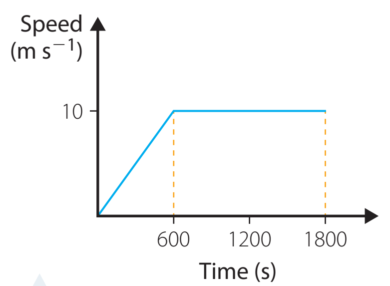

FIGURE 15.4.5

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ANALYSING

7 A spring of stiffness k and natural length ℓ is compressed so that its length becomes L. Express Hooke's law for this spring in terms of L and ℓ. Rewrite this expression for the case when the spring is extended to a length L.

8 A spring lies on a horizontal table. It has a natural length of 45 cm and a stiffness of 200 N m^{-1}. It is compressed to a length of 20 cm and a projectile of mass 200 g is placed on the end. The spring is then released.

a Sketch the situation.

b Draw the force–extension graph for this spring.

c On the graph, indicate how to measure the energy stored in the spring.

d Calculate the speed at which the projectile is released.

15.5 Elastic and inelastic collisions

15.5.1 Collision lab

The total kinetic energy immediately before a collision occurs is *sometimes* equal to the total kinetic energy immediately after the collision has concluded. Once the kinetic energies of all the particles in a collision are added up immediately before and immediately after a collision, they can be compared. If they are the same before and after the collision, then the kinetic energy has been conserved because it has all been returned. For example, a spring can be compressed by a moving object until it stops. All this energy can be stored, then released.

KEY FORMULA

Elastic collision:

$$\sum E_k\,(\text{before}) = \sum E_k\,(\text{after})$$

$$\Rightarrow \sum\left(\tfrac{1}{2}mv^2\right)_{\text{before}} = \sum\left(\tfrac{1}{2}mv^2\right)_{\text{after}}$$

KEY FORMULA

Inelastic collision:

$$\sum E_k\,(\text{before}) \neq \sum E_k\,(\text{after})$$

$$\Rightarrow \sum\left(\tfrac{1}{2}mv^2\right)_{\text{before}} \neq \sum\left(\tfrac{1}{2}mv^2\right)_{\text{after}}$$

Solving problems: elastic and inelastic collisions

To solve collision questions involving energy and momentum, use the 'Before' and 'After' column arrangement outlined on pages 309–10.

The total kinetic energy before and after can then be added into the columns and compared. Once the total kinetic energy of all the particles involved before and after the collision has been calculated, a decision can be made as to whether the collision is:

- elastic – both values are the same
- inelastic – the values are different.

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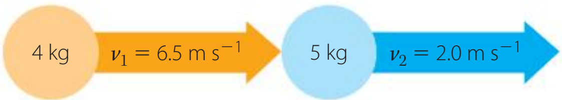
WORKED EXAMPLE 15.5.1

A 4.0 kg mass travelling to the right at 6.5 m s^{-1} collides with a 5.0 kg mass moving to the right at 2.0 m s^{-1}. They stick together and move off at a speed of 4.0 m s^{-1}.
Decide whether the collision is elastic or inelastic.

ANSWER

BEFORE

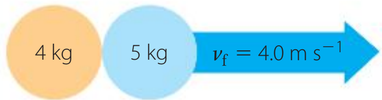


$$\sum E_k\,(\text{before}) = \tfrac{1}{2}\left[4.0\,\text{kg} \times \left(6.5\,\text{m s}^{-1}\right)^2\right] + \tfrac{1}{2}\left[5.0\,\text{kg} \times \left(2.0\,\text{m s}^{-1}\right)^2\right]$$

$$\sum E_k\,(\text{before}) = 84.5\,\text{J} + 10\,\text{J}$$

$$\sum E_k\,(\text{before}) = 94.5\,\text{J}$$

AFTER



$$\sum E_k\,(\text{after}) = \tfrac{1}{2}\left[9.0\,\text{kg} \times \left(4.0\,\text{m s}^{-1}\right)^2\right]$$

$$\sum E_k\,(\text{after}) = 72.0\,\text{J}$$

$$\sum E_k\,(\text{before}) \neq \sum E_k\,(\text{after})$$

The collision is inelastic.

Combining energy and momentum analyses

Impulse–momentum or work–energy concepts and equations can be used together to analyse a collision. This is because these two ways of analysing motion relate to the same situation. A complete analysis of a collision includes finding values for force, distance, time and velocity. Impulse–momentum analysis is used when the data involves force, time and velocity. Work–energy analysis is used when the data involves force, distance and velocity. The analyses can be combined to completely analyse the motion. Two important points need to be emphasised:

- The total momentum immediately before a collision occurs is *always* equal to the total momentum immediately after the collision has concluded (law of conservation of momentum).
- The total kinetic energy immediately before a collision occurs is *sometimes* equal to the total kinetic energy immediately after the collision has concluded.
  - Elastic collision: $\sum E_k\,(\text{before}) = \sum E_k\,(\text{after})$

    $$\Rightarrow \sum\left(\tfrac{1}{2}mv^2\right)_{\text{before}} = \sum\left(\tfrac{1}{2}mv^2\right)_{\text{after}}$$

  - Inelastic collision: $\sum E_k\,(\text{before}) \neq \sum E_k\,(\text{after})$

    $$\Rightarrow \sum\left(\tfrac{1}{2}mv^2\right)_{\text{before}} \neq \sum\left(\tfrac{1}{2}mv^2\right)_{\text{after}}$$

These analytic techniques are used to understand car crashes. The longer it takes, in terms of time and distance, for a car to come to a stop, the smaller the force that is applied to the occupants.

SCIENCE AS A HUMAN ENDEAVOUR

Compulsory seatbelt legislation, which was first introduced in 1972, along with the later introduction of crumple zones, airbags and air curtains, have significantly reduced car accident injuries and deaths. This is because the forces applied to occupants are reduced by increasing the time and distance before the occupant, moving with the vehicle, comes to a stop.

Research the testing techniques used to develop safety ratings for vehicles (ANCAP), the child restraint evaluation program (CREP) or the development of car safety ratings. Consider side, frontal and oblique impact tests.

INQUIRING FURTHER

The lobes of the brain can be seriously affected in car accidents. If the head of an unrestrained person travelling at 75 km h^{-1} hits the windscreen, the forehead bone will be crushed in by about 8.5 cm. The impact is transmitted through the brain fluids to the back of the brain where it reflects. A large amount of energy acts on the back of the head as well as on the front. Blood vessels burst, causing swelling in the confined space of the bony skull. All this has serious effects. People with acquired brain injury have great difficulty with physical movement, coordination, relationships, thinking and control of behaviour.

On a blank template showing a cross section of a person's head, identify the brain's lobes and the damage that could be produced in a 75 km h^{-1} impact with the windscreen.

Produce a poster that demonstrates the possible effects on the person's functioning as a result of the collision.

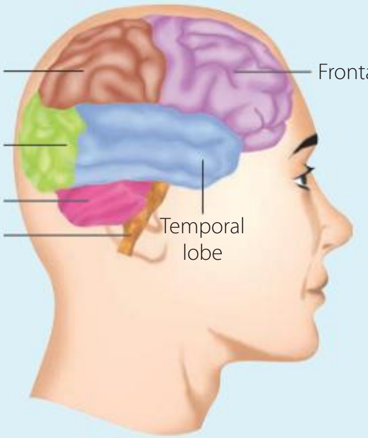


FIGURE 15.5.1 Parts of the human brain

15.5.2 Brain Injury Australia

15.5.3 Acquired brain Injury

When solving problems involving a combination of work–energy and impulse–momentum analyses, it is useful to first identify the data available:

- If *displacement* (s) data is initially provided, use work–energy, then impulse–momentum.
- If *time* (t) data is initially provided, use impulse–momentum then work–energy.

WORKED EXAMPLE 15.5.2

A 75 kg person in a 2.0×10^3 kg vehicle is travelling at 14 m s^{-1} when it crashes into a wall. The vehicle crumples by 0.50 m before coming to a stop on the wall.

a Calculate the average force applied by the wall on the car.

b Calculate the time taken for the car to come to a stop.

c Determine the force applied by the seatbelt on the person.

ANSWERS

a Use work–energy analysis because the data includes force, displacement and velocity:

$$W(\text{by wall on car}) = F(\text{by wall on car}) \times s$$

$$\Rightarrow F(\text{by wall on car}) = \frac{W(\text{by wall on car})}{s}$$

$$\Rightarrow F(\text{by wall on car}) = \frac{^{-}1.96 \times 10^5\ \text{J}}{0.5\ \text{m}}$$

$$\Rightarrow F(\text{by wall on car}) = {}^{-}3.9 \times 10^5\ \text{N}$$

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b Use impulse–momentum analysis to find the time interval, t:

$$J = Ft = mv_f - mv_i$$

$$\Rightarrow F(\text{by wall on car}) \times t = m(v_f - v_i)$$

$$\Rightarrow t = \frac{m(v_f - v_i)}{F(\text{by wall on car})}$$

$$\Rightarrow t = \frac{2.0 \times 10^3\ \text{kg} \times (0\ \text{m s}^{-1} - 14\ \text{m s}^{-1})}{-3.9 \times 10^5\ \text{N}}$$

$$\Rightarrow t = 7.2 \times 10^{-2}\ \text{s}$$

c The person stops at the same rate as the vehicle. Impulse–momentum or work–energy can be used to find the force, F, applied by the seatbelt on the person.

Impulse–momentum:

$$Ft = mv_f - mv_i$$

$$\Rightarrow Ft = m(v_f - v_i)$$

$$\Rightarrow F = \frac{m(v_f - v_i)}{t}$$

$$\Rightarrow F = \frac{75\ \text{kg} \times (0\ \text{m s}^{-1} - 14\ \text{m s}^{-1})}{7.2 \times 10^{-2}\ \text{s}}$$

$$\Rightarrow F = {}^{-}1.5 \times 10^4\ \text{N}$$

Work–energy

$$Fs = \tfrac{1}{2}mv_f^2 - \tfrac{1}{2}mv_i^2$$

$$\Rightarrow Fs = \tfrac{1}{2}m(v_f^2 - v_i^2)$$

$$\Rightarrow F = \frac{\tfrac{1}{2}m(v_f^2 - v_i^2)}{s}$$

$$\Rightarrow F = \frac{\tfrac{1}{2} \times 75\ \text{kg} \times \left[(0\ \text{m s}^{-1})^2 - (14\ \text{m s}^{-1})^2\right]}{0.5\ \text{m}}$$

$$\Rightarrow F = {}^{-}1.5 \times 10^4\ \text{N}$$

PRACTICAL ACTIVITY 15.5.1

Newton's cradle

Elastic collisions are characterised by equal kinetic energies before and after the collision. A Newton's cradle comprises several hard metal balls, independently hung and just touching each other. When one or more balls are released to collide with the remainder, a nearly elastic collision may be observed.

FIGURE 15.5.2 Newton's cradle

INTRODUCTION

The purposes of this practical activity are to demonstrate:

- conservation of energy
- elastic collisions
- the conservation of momentum.

MATERIALS

- Newton's cradle comprising at least five balls of equal mass (mass, m, of 1 ball = 1 unit)
- ruler
- motion-measuring device such as a motion sensor or video camera

PROCEDURE

1 Set up the cradle and motion-measuring system.
2 Draw back one ball to a measured height.
3 Release the ball (incoming ball).
4 Record the interaction.
5 Measure the height to which the ball (outgoing ball) at the other end rises.
6 Repeat by drawing back two, three and four balls.
7 Record all data in a correctly constructed data table.

RESULTS

1 From the height data, calculate the velocity of the:
   a incoming ball(s) at impact.
   b outgoing ball(s) as they start to rise.
2 From the velocity data, calculate:
   a the kinetic energy of
      i incoming ball(s) at impact
      ii outgoing ball(s) at the moment they start to rise.
   b the momentum of:
      i incoming ball(s) at impact
      ii outgoing ball(s) at the moment they start to rise.
3 Estimate the uncertainty in the measurements of height and the effect of the uncertainties in the calculated velocities.

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DISCUSSION

1 Within the limits of uncertainty, indicate the extent to which the following were, or were not, demonstrated:
- conservation of energy
- elastic collisions
- conservation of momentum.

2 Explain how conservation of energy was assumed in order to calculate the velocities of the incoming balls.

3 Explain why there was no need to measure the mass of the balls in grams.

4 Identify the unit used in this experiment to measure energy and momentum (the units are not joule and $kg\,m\,s^{-1}$ respectively).

5 Identify any energy losses and ways to reduce these.

6 Explain what you would need to do to measure the energy of a 'click' produced when two balls collide using this apparatus and method.

SECTION REVIEW 15.5

REMEMBERING

1 Define:
- a elastic collision
- b inelastic collision.

2 In analysing a collision, identify the quantity that is:
- a always conserved
- b only conserved for elastic collisions.

UNDERSTANDING

3 Identify the starting concepts for analysis of collisions involving:
- a time-interval data
- b displacement data.

4 Compare the conservation of momentum and energy transfers from the start to the end of an elastic collision.

APPLYING

5 A 4.0 kg mass, P, sliding to the right at $3.0\,m\,s^{-1}$ collides with a 5.0 kg mass, Q, moving to the left at $2.0\,m\,s^{-1}$. P moves off at $1.0\,m\,s^{-1}$ to the left. The collision takes 0.4 s.
- a Calculate the velocity of Q after the collision.
- b Calculate the force applied by P on Q.
- c State whether the collision is elastic or inelastic.

6 A vehicle travelling at $10\,m\,s^{-1}$ comes to a sudden stop. It crumples by a distance of 1.0 m. For a 100 kg passenger wearing a seatbelt, calculate:
- a the force applied by the seatbelt on the person
- b the time taken for the person to come to a stop.

ANALYSING

7 Explain how a Newton's cradle can be used to demonstrate elastic collisions.

CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 Explain how work and energy are related.

2 Define 'work' in terms of force and distance. Indicate the conditions under which work is done.

3 Use graphs to show how to calculate the potential energy stored in a system involving:
   a a small mass near Earth's mass
   b a spring.

4 For a spring, it is usual to draw F–x graphs in the first quadrant. Explain what F and x refer to.

CATEGORY QUESTIONS

5 Describe the conditions for which the law of conservation of energy applies.

6 Draw up 'Before' and 'After' columns for a linear collision between two objects that travel towards each other, then bounce off each other in opposite directions. Into each column write the equations for impulse, momentum and kinetic energy.
   a Write equations that link before and after quantities for:
      i momentum
      ii kinetic energy.
   b Show how to decide if the collision is elastic or inelastic.

7 Compare elastic and inelastic collisions. Give two examples of each.

8 Explain why a falling mass near Earth can be considered to be a collision.

ELABORATION QUESTIONS

9 Explain the physics behind the equation $v_{max} = \sqrt{2gh_{max}}$.

10 Explain why the potential energy changes for a ball thrown from one person to another are the same as for a ball thrown vertically up to the same maximum height.

EVIDENCE QUESTIONS

11 'When it comes to analysing collisions, impulse and work amount to the same thing.' Discuss.

12 Cars A and B, travelling at relatively fast speeds, are crashed into a wall and come to a stop on the wall. They both carry identical dummy passengers that are securely fitted with seatbelts. Car A is rigid and has very little damage. Car B crumples significantly on impact. Both dummies experience the same loss of kinetic energy. The dummy passenger in car A is severely damaged but the dummy passenger in car B experiences much less damage.
   a Explain why the two dummies experience the same loss of kinetic energy.
   b Select some reasonable data about mass of dummies, speed of cars and distances over which crashes occur to explain, quantitatively, why the effect on the dummies is so different.

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END-OF-CHAPTER EXAM

End-of-chapter test

1 A ball is thrown upwards. The gravitational potential is stored in:

A the ball.

B the Earth.

C the ball–Earth system.

D the loss of kinetic energy of the ball.

2 How much energy is stored in a spring of stiffness 350 N m^{-1} when it is compressed by 0.25 m?

A 11 J

B 22 J

C 44 J

D 88 J

3 How much kinetic energy is gained by a 4.5 kg mass when it is thrown downwards at 2.0 m s^{-1} from a height of 12.3 m to the ground?

A 4.5 J

B 9.0 J

C 551 J

D 560 J

4 How much work is done on a car of mass 800 kg when it accelerates uniformly from 14 m s^{-1} to 30 m s^{-1} in 3.0 s?

A 1.0×10^5 J

B 2.0×10^5 J

C 2.8×10^5 J

D 3.6×10^5 J

5 At any time in a collision between two objects:

A momentum but not kinetic energy is conserved.

B kinetic energy but not momentum is conserved.

C kinetic energy and momentum are both conserved.

D neither kinetic energy nor momentum are conserved.

6 Describe four necessary conditions which must be present if the law of conservation of energy strictly applies.

7 Figure 15.6.1 shows how the net force applied to a boat being winched towards a boat ramp varies with distance. The boat travels at 2.0 m s^{-1}. There is a constant friction force of 30 N.

a Calculate the work done by the net force during the first 12 m.

b Find the work done by the winch after 36 m of effort.

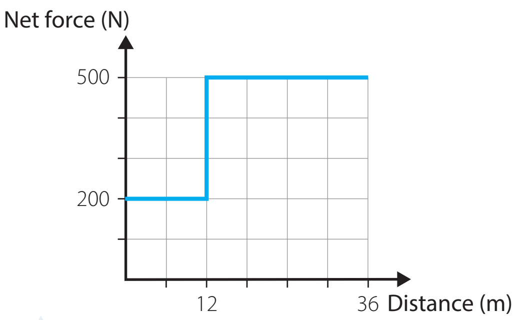

FIGURE 15.6.1

8 During a competition, the centre of mass of a 60 kg high jumper rises from 0.63 m to 1.8 m above the ground. The top of the landing pit is 0.42 m above the ground.

a Calculate the change in potential energy of the system.

b Find the speed with which the high jumper left the ground.

c Calculate the kinetic energy of the high jumper when landing in the pit.

9 In an experiment to verify Hooke's law, a force was applied to a spring and the extension measured. The following data were collected.

Force applied to spring (N)	20	40	50	60
Extension (cm)	15	31	38	46

a Plot the data on a graph so as to show that the spring obeys Hooke's law.

b Find the force constant for the spring in SI units.

c Shade the graph to show the energy stored in the spring when it is stretched from 20 cm to 40 cm.

d Calculate the energy stored in the spring when it is stretched from 20 cm to 40 cm.

10 In a test crash at 20 m s^{-1}, the head of an 8.0 kg unrestrained crash dummy is smashed in by 5.0 cm by the windscreen.

a Calculate the average force applied to the head of the crash dummy.

b Find the time taken for the crash dummy to be damaged by the windscreen.

11 Use concepts of work and energy to explain how crumple zones and seatbelts help reduce injury and death of occupants in cars.

12 Explain why the law of conservation of momentum applies throughout a collision but the conservation of kinetic energy relates only to one form of collision.

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» TOPIC 2

LINEAR MOTION AND WAVES

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Topic 2: Waves

The topic 'Waves' introduces students to mechanical and electromagnetic waves and the associated wave phenomena of reflection, refraction, diffraction, superposition, total internal reflection, interference and polarisation. Related terminology including wavelength, amplitude, period and frequency will be defined and interpreted alongside waveform representations of transverse and longitudinal waves. Sound and light waves will be studied, including standing wave formations, resonance, natural frequency and intensity. Ray diagrams will be used to demonstrate reflection and refraction of light, while formulas will be applied to solve problems involving light intensity and the refraction of light at boundaries between media. Practical skills in obtaining, tabulating, graphing and analysing data for determining the refractive index of a transparent substance are also addressed.

SCIENCE AS HUMAN ENDEAVOUR

Students should be give opportunities to investigate how a knowledge and understanding of the types and properties of waves enable scientists to predict tsunamis; an understanding of wave behaviour can be used by engineers to reduce noise pollution; the continued development of the wave theory of light.

KEY FORMULAS

$$v = f\lambda$$

$$f = \frac{1}{T}$$

$$L = n\frac{\lambda}{2}$$

$$L = (2n-1)\frac{\lambda}{4}$$

$$\frac{\sin i}{\sin r} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2} = \frac{n_1}{n_2}$$

$$I \propto \frac{1}{r^2}$$

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16 WAVE PROPERTIES

Introduction

Our investigations into the movement of objects up to this point has focused entirely upon motion in straight lines. It turns out, however, that almost all motion is more correctly described, at least at a fundamental level, by movement in a periodic form, also known as wave motion.

Sound waves, seismic waves, light and even particles all have wave properties that cannot be entirely described with the classical Newtonian laws of motion. In this chapter, we will investigate the features of waves that require a medium to travel through, and their behaviour when they interact with everyday objects.

Stimulus questions

- What is a wave?
- How does a wave transport energy?
- Do ocean waves transport water from the deep ocean to the shore?
- How is it possible to hear sound around a corner?
- How does a musical instrument use waves to produce a note?

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16.1 Waves transfer energy

There are many types of waves. A stone dropped into a pond of water creates a circular wave that will spread out in a circle (Figure 16.1.1). A string held taut and vibrated at one end will form waves that travel through the string from one end to the other. Sound energy can be carried to our ears through any medium by sound waves. Seismic waves from explosions and earthquakes travel through Earth, and can give scientists an insight into what lies beneath its surface. Light waves can travel through the vacuum of space and tell us about the content of distant stars.

FIGURE 16.1.1 Concentric circular waves formed when a stone is dropped into water

Despite the many differences between different kinds of waves, they all have one feature in common: all waves transfer energy from one place to another.

Since a wave is a travelling phenomenon that causes multiple points to move simultaneously, it is difficult to calculate the energy of a wave. Instead, we define the **intensity** of the wave as the rate at which energy is carried by the wave. It has units of watts per square metre ($W m^{-2}$) and is known to be proportional to the square of the **amplitude** (A) or maximum displacement of a particle in a wave.

intensity
a measure of the energy per unit time travelling through a unit area perpendicular to the direction of travel

amplitude
the maximum displacement of a particle in a wave from its mean position; units: m

A wave will travel out in all directions from its source in a three-dimensional sphere. As the wave moves outwards, the energy that was emitted from the source becomes spread over a larger spherical surface (Figure 16.1.2). As a result, the intensity of the wave decreases as the wave gets further from the source.

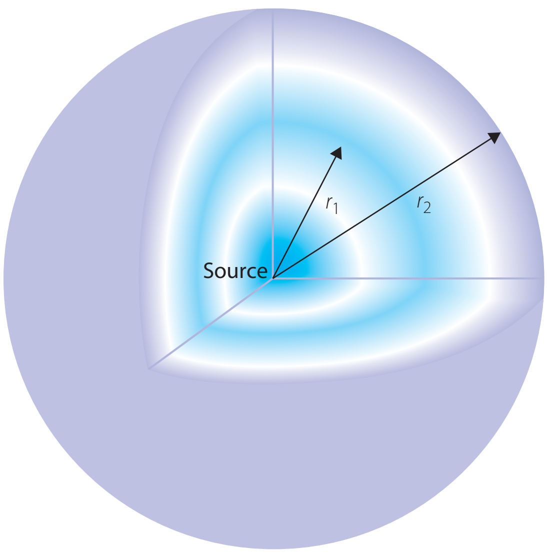

FIGURE 16.1.2 A wave travelling outwards from a source in three dimensions forms a sphere.

SECTION REVIEW 16.1

REMEMBERING

1 What feature do all waves have in common?

2 Define 'intensity' as it applies to travelling waves.

UNDERSTANDING

3 Explain what happens to the intensity of a wave when its amplitude is doubled.

ANALYSING

4 Examine Figures 16.1.1 and 16.1.2 and establish a reason why waves on a pond surface appear as circles if waves are known to travel as spheres.

16.2 Mechanical waves

mechanical waves waves that require a physical substance to be able to propagate

medium a substance that allows the transfer of energy from one place to another

16.2.1 Mechanical waves

If an ocean wave is observed moving towards the shore, it would be easy to make the incorrect assumption that it was carrying water from far out at sea towards the land. Water waves, together with sound waves, seismic waves and waves on a string are termed **mechanical waves**, and all require a **medium** to travel through. They do not transport the whole medium from place to place but, rather, the particles of the medium oscillate around their rest position.

FIGURE 16.2.1 Ocean waves may appear to bring water from out at sea, but this is not so.

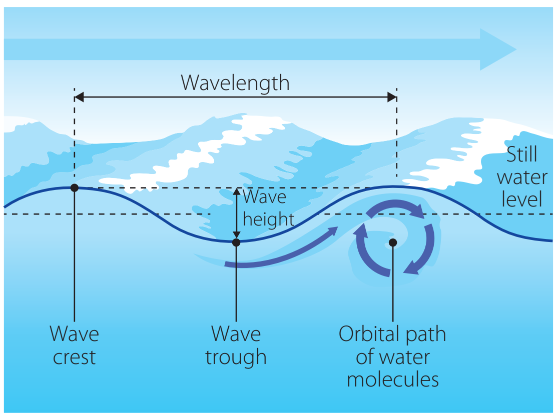

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FIGURE 16.2.2 Ocean waves are caused by the movement of water particles below the surface of the wave. The particles stay in orbits and do not travel forwards with the wave.

wavefront an imaginary surface joining all points in space that are reached at the same instant by a wave propagating through a medium

ray a line drawn at right angles to a wavefront and in the direction of travel

ray model a model that describes light as travelling in rays that change direction during interactions with matter

Mechanical waves travel in a material medium made of interconnected particles that are progressively disturbed. Energy, but not particles, is transferred through the medium.

We can describe a wave using the ideas of wavefronts and rays. A **wavefront** is a surface joining all points in space that are reached at the same instant by a wave propagating through a medium. A **ray** is a line drawn at right angles to the wavefront in the direction of propagation. This description is called the **ray model**.

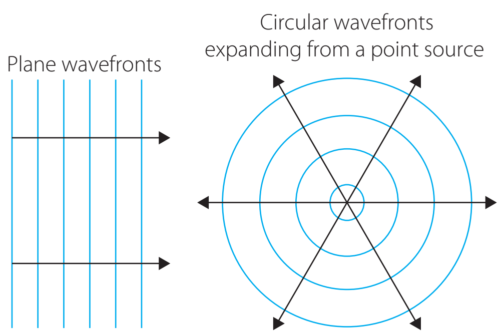

FIGURE 16.2.3 Wavefront models of waves. The arrows represent the direction of propagation of the wavefronts.

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SECTION REVIEW 16.2

REMEMBERING

1 Define 'mechanical wave'.

2 Define 'wavefront'.

3 Recall the importance of a medium to the propagation of mechanical waves.

UNDERSTANDING

4 Describe the motion of a medium as a mechanical wave passes through it.

5 Classify the ocean waves shown in Figure 16.2.1 as plane wavefronts or circular wavefronts and explain your answer.

16.3 Wave types

Pulses

Figure 16.1.1 (page 351) shows that a stone that drops into a body of water creates surface disturbances that radiate from the point where the stone broke the water. The leading edge of the entire wave forms a circle that is the wavefront. If only a single wavefront passes through a medium it is called a **pulse**.

pulse
a single wavefront travelling through a medium

A single pulse on a string can be created by quickly moving your hand up and down (Figure 16.3.1). When the hand pulls up on the end of the rope, the section of the rope that is immediately next to the end section feels a force and begins to move up as well. This continues for each adjacent section as the wave pulse moves along the string. When the hand moves back down to the original position, the section next to the hand feels a force back down and begins to move downwards, and so forth. The original source of the wave was therefore a disturbance and the forces holding the rope together cause the pulse to travel.

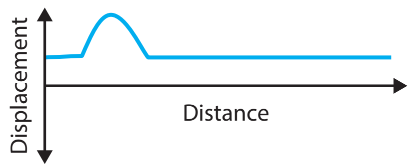


FIGURE 16.3.1 Representation of a wave pulse in a stretched string or spring

Continuous waves

If stones are dropped in water in a regular pattern, wavefronts are produced continuously. A **continuous wave** moves outwards at a constant speed in all directions. The source of such waves must be a disturbance that is continuous and oscillating, in other words, a vibration. As can be seen in Figure 16.3.2, a hand oscillates one end of a rope up and down repeatedly and results in a continuous wave traveling to the right along the rope.

continuous wave
repeating waves passing through a medium

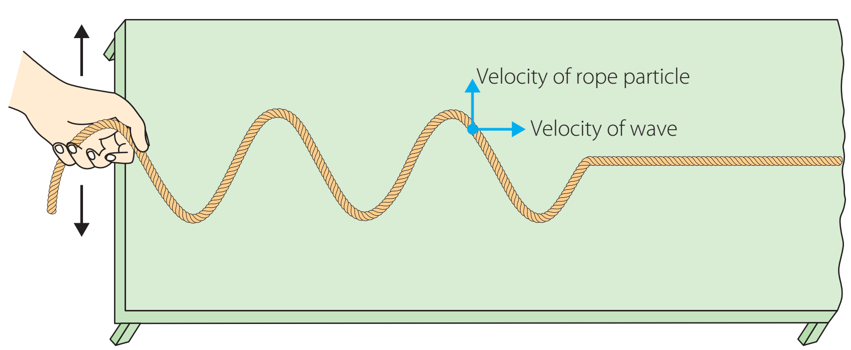


FIGURE 16.3.2 Representation of a continuous wave on a rope arising from a vibrating disturbance

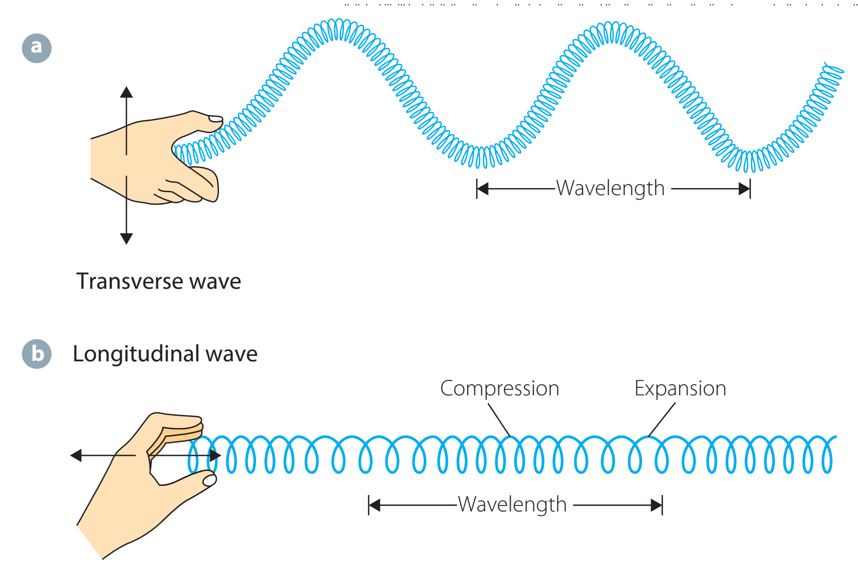
16.1.1 Wave types I: This simulation will allow you to create and compare pulses and continuous waves on a string.

transverse wave
a wave whose particles oscillate about a mean position perpendicular to the direction of travel by the wave

Transverse waves

If the end of a stretched slinky spring is moved up and down relative to the length of the slinky, a wave will move down its length. The particles of the slinky vibrate up and down in a direction that is transverse (at right angles) to the motion of the wave. This type of wave is called a **transverse wave**.

FIGURE 16.3.3 (**a**) In a transverse wave, particles oscillate about a mean position perpendicular to the direction of travel by the wave. (**b**) In a longitudinal wave, particles oscillate around a mean position in the same line as the direction of travel of the wave.

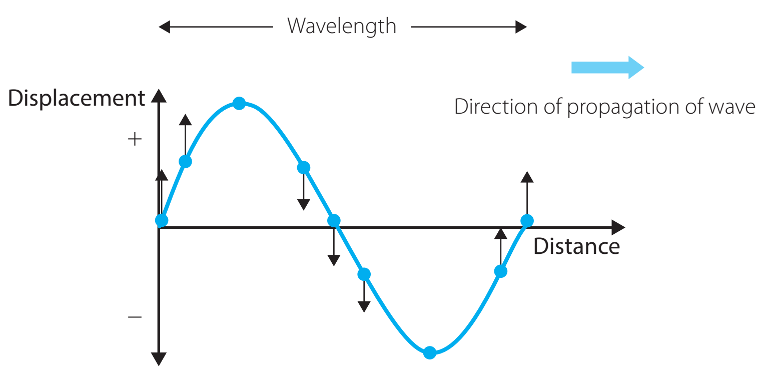


crest
the positive peak of a wave; units: m

trough
the negative peak of a wave; units: m

In a transverse wave, individual particles of the medium move up and down about their rest position. A series of wave **crests** and wave **troughs** moves through the medium. A graph of the position of particles along the medium at one particular time looks like a sine graph (Figure 16.3.4).

FIGURE 16.3.4 A displacement versus distance graph of a transverse mechanical wave showing the position of the particles at an instant in time



longitudinal wave
a wave whose particles oscillate about a mean position in the same line as the direction of travel of the wave

compression
a region of high pressure in a mechanical wave

rarefaction
a region of low pressure in a mechanical wave

At a crest or a trough, particles are stationary and about to move towards the mean position. Particles on either side of the crest or trough are moving away from or towards the mean position.

Longitudinal waves

Longitudinal waves can be created by quickly pushing and pulling on the end of a stretched slinky. In a longitudinal wave the motion of the particles of the medium is along the line of the direction of travel by the wave. In this type of wave, there is a series of **compressions** and **rarefactions**, as shown in Figure 16.3.3(b).

Particles move back and forth in the same line as the direction of the transfer of energy. The further away from the mean position a particle moves before returning, the greater the amplitude of the disturbance.

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When the particles around a point are all moving towards the point, there is a local compression. If they are all moving away from the point, there is a local rarefaction. A particular point in the medium through which the wave disturbance is travelling experiences a series of compressions and rarefactions (changes to the undisturbed pressure) as the energy passes through it. Figure 16.3.5 shows a snapshot at an instant in time of where the particles along the top have been displaced to as the wave passes.

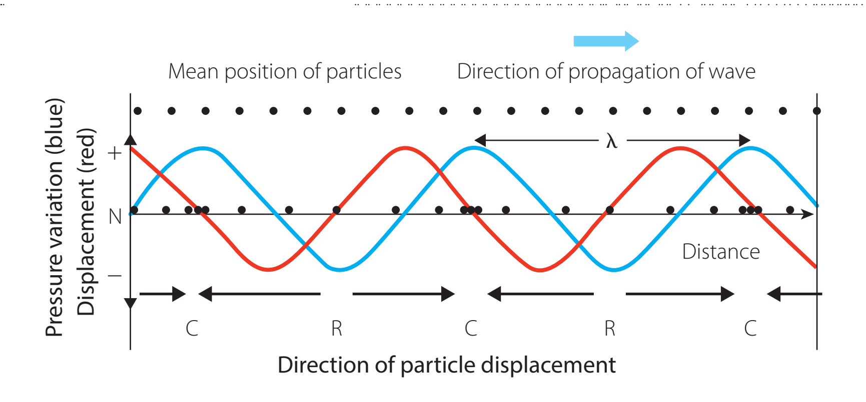

FIGURE 16.3.5 Longitudinal wave showing rarefactions (R) and compressions (C) in a medium at the same time

16.3.1 Transverse and longitudinal waves

16.3.2 Longitudinal and transverse wave motion

Figure 16.3.5 also shows how the air pressure varies. Maximum pressure occurs when the particles are most constrained (blue), hence displaced little. The pressure is lowest when the displacement of particles from their mean positions (red) is greatest (Figure 16.3.5).

SECTION REVIEW 16.3

REMEMBERING

1 Define the following terms.
- **a** Pulse
- **b** Continuous wave
- **c** Compression
- **d** Rarefaction

UNDERSTANDING

2 Compare the motion of a particle in a medium that is transmitting a transverse wave with that of a medium transmitting a longitudinal wave.

3 Compare the nature of a disturbance that will form a pulse on a string with that which will form a continuous wave.

16.4 Examples of waves

Transverse waves occur when the particles of the medium through which a wave is travelling oscillate about a mean position in a direction that is perpendicular to the direction of the wave itself. There are many examples of this in nature, including vibrations on stringed instruments, surface waves on water (or at least, they can be modelled like this) and seismic (earthquake) S waves.

Longitudinal waves are caused by the transfer of energy in the form of compressions and rarefactions through a medium in line with the direction of wave travel. Examples of longitudinal waves include sound waves and seismic P waves.

16.4.1 Geoscience Australia earthquakes

FIGURE 16.4.1
Transverse waves travelling on a violin string can be seen to be oscillating in a direction perpendicular to the string itself.

Vibrations on stringed instruments

Whenever the strings of a musical instrument are plucked (guitar and harp), bowed (violin, cello or double bass) or struck (piano), the initial disturbance results in a portion of the string being displaced in a direction that is transverse to the string itself.

The particles in this position of initial displacement will cause their adjacent particles to feel a force and will displace them as well. These will then cause the displacement of their adjacent particles and so on. In this way, a wave will travel along the string.

Surface waves on water

As previously mentioned, waves travelling on the ocean do not transport large volumes of water towards the shore. Instead, as can be seen in Figure 16.2.2 (page 352), the water particles essentially oscillate in a direction that is perpendicular to the direction of travel of the wave. In actual fact, they move in circles below the surface, but are still move transverse waves.

16.4.2 Waves on a string

Sound waves

16.4.3 Sound

In a sound wave, particle oscillations are always parallel to the direction of energy flow; therefore, sound waves are longitudinal waves. When sound travels through a medium, the particles form a series of compressions and rarefactions (Figure 16.4.2(a)). At compressions, the pressure of the medium is higher than the normal pressure. At rarefactions, the pressure is lower than normal. This can be seen in a graph of pressure variation against the distance from the source (Figure 16.4.2(b)).

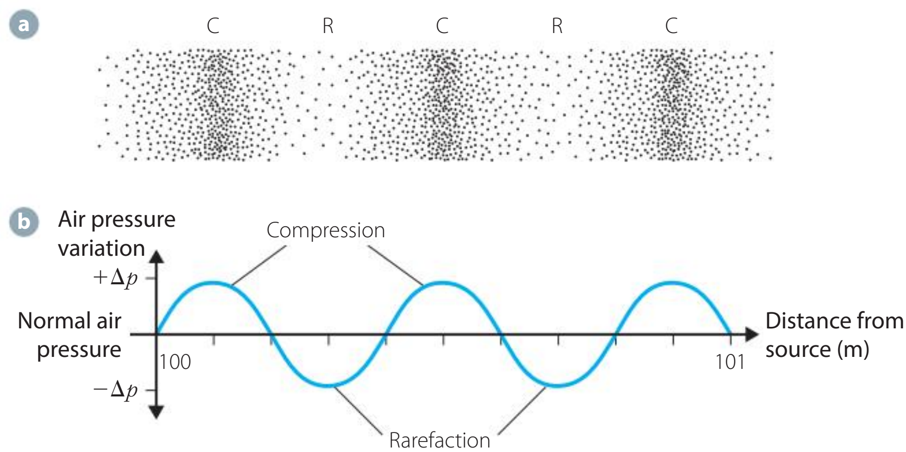

FIGURE 16.4.2 (**a**) When sound travels through a medium, the particles form a series of compressions and rarefactions. (**b**) The graph shows pressure variation with distance.

When a sound wave strikes the ear (Figure 16.4.3), the pressure changes between the compressions and rarefactions cause the ear drum to move in and out. This motion is then transferred to the three bones of the middle ear and on to the fluid of the cochlea in the inner ear. The movement of this fluid causes small hairs on the surface of the cochlear to vibrate, which ultimately creates the nerve pulses that our brain recognises as sound.

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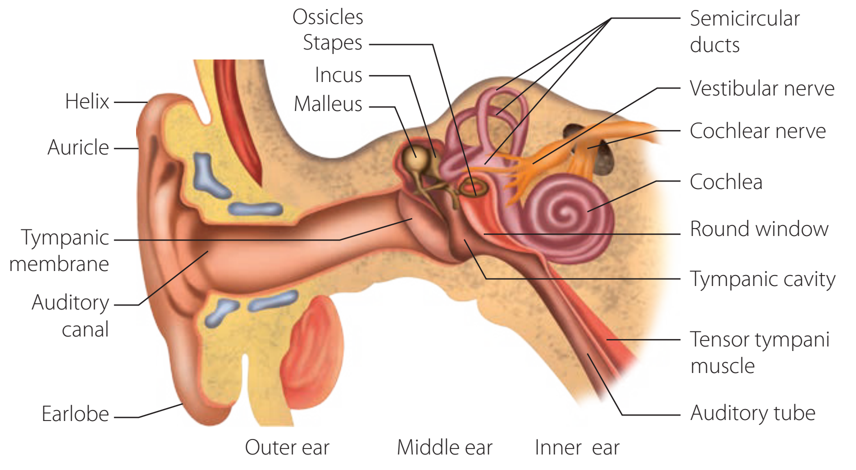


FIGURE 16.4.3 Physiology of the ear. Vibrations are passed on from air entering the ear canal, through the middle ear and into the inner ear. From here nerve pulses are passed on to the brain.

Seismic waves

The outer layer of Earth is made up of tectonic plates. Earthquakes happen when these plates catch when slipping past one another. The pressure builds up at the catch points as the plates continue to press on each other. When the pressure gets too great, the rock gives way and the plates suddenly slip past each other with a jolt. The stored energy is released abruptly. Vibrations travel as shockwaves (seismic waves) through Earth's interior.

These seismic waves radiate in all directions from the point underground where the energy was released. This point is known as the **seismic focus**. Directly above this is the earthquake's **epicentre** – the point on Earth's surface where the earthquake will be experienced most strongly. If this is in an inhabited area it is the point at which the most damage is done.

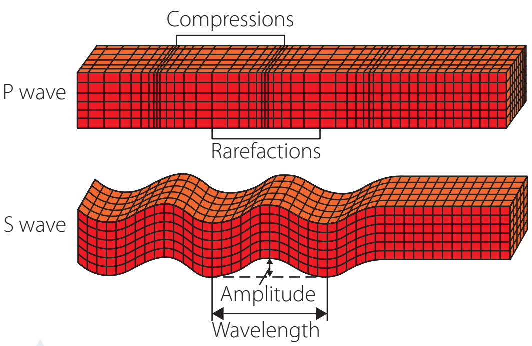


FIGURE 16.4.4 Propagation of longitudinal primary (P) and transverse secondary (S) shear waves

Waves that propagate within the ground are called **body waves.** There are two types of body waves: the primary or **P waves** and the secondary or **S waves**. Primary (P) waves are longitudinal compression waves (sound waves). Secondary (S) waves are transverse waves; they are also called shear waves. Their velocities vary with the density of the rock they pass through. The density of rock increases with depth due to the pressure of the rock above. This means the speed of the waves increases with depth. Different rock composition also affects the speed of the waves. This density gradient refracts the waves back up to the surface in a curved concave path, where they can be recorded on a **seismograph**.

seismic focus the underground point from which earthquake energy is released

epicentre the point on the Earth's surface directly above the seismic focus

body waves seismic waves that travel through the body of Earth

P wave longitudinal earthquake compression waves that pass through the body of Earth

S (or shear) wave transverse earthquake waves that shake Earth in directions which are perpendicular to the direction that the wave is travelling; also known as shear waves

seismograph a device that records the amplitude and frequency of seismic waves and yields information about Earth and its subsurface structure

SECTION REVIEW 16.4

REMEMBERING

1 Identify each of the following waves as transverse or longitudinal.

- **a** Sound waves
- **b** Seismic S waves
- **c** Seismic P waves
- **d** Waves on a stringed instrument
- **e** Surface water waves

2 Define:
   a compression
   b rarefaction.

UNDERSTANDING

3 Outline how waves are produced in a stringed instrument.
4 Outline how surface water waves are produced.
5 Outline the way in which sound is transported from the air into the ear so that it is received as the sensation of sound.
6 Compare the properties of seismic S and P waves. What causes their formation?

ANALYSING

7 Analyse the structure of the ear presented in Figure 16.4.3 (page 357) to suggest some common causes of deafness.
8 Analyse the behaviour of waves in different types of rock to suggest a way in which a seismograph may be used to examine the inner composition of the Earth.

16.5 Wave features

displacement the straight-line distance between the current position of a particle in a wave and its mean position

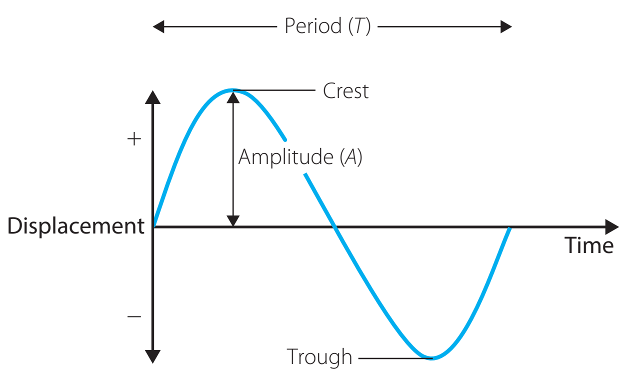
sinusoidal pattern a pattern that is similar in shape to that of a sine wave

The behaviour of mechanical waves can be graphed on either a **displacement** versus time graph or on a displacement versus distance graph. Both graphs will give a **sinusoidal pattern**; however, each graph shows different features of the wave and gives slightly different information about the wave.

Displacement versus time graph

A displacement–time graph (Figure 16.5.1) shows the displacement from the mean position of a single particle in the medium as it changes over time. It is very useful for finding the amplitude and period of a wave and can be extended to find the frequency.

FIGURE 16.5.1 A displacement versus time graph of a mechanical wave represents the displacement of one particle of the medium experiencing a wave disturbance over time. It also shows the amplitude of the wave.



period (T) the time it takes before a wave repeats itself; units: s

frequency (f) the number of whole waves of cycles in one second; units Hz

KEY FORMULA

The frequency of a wave

$$f = \frac{1}{T}$$

Where:
f = frequency (Hz)
T = period (s)

The **period (T)** of a wave is the time it takes before a wave repeats itself and amplitude (A) is the largest distance of the particle from the mean position before returning. The top of the wave is called a crest and the bottom a trough.

The **frequency (f)** of a wave is the number of crests generated in a time interval. The unit of frequency is the hertz, Hz. As one period is the time it takes to complete one full wave, the inverse of the period is the number of full waves per second, the frequency.

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WORKED EXAMPLE 16.5.1

It is observed that once the crest of one ocean wave passes a point, it takes 3.0 s for the next crest to arrive at the same point. Calculate the frequency of the waves.

ANSWER

Use the frequency equation:

$$f = \frac{1}{T}$$

Insert known values:

$$f = \frac{1}{3\,\text{s}}$$

$f = 0.3333\,\text{s}^{-1}$

Give the answer with the correct units and number of significant figures:

$f = 0.33\,\text{Hz}$

WORKED EXAMPLE 16.5.2

Analyse the wave features in Figure 16.5.2 and calculate the wave's:

a amplitude

b period

c frequency.

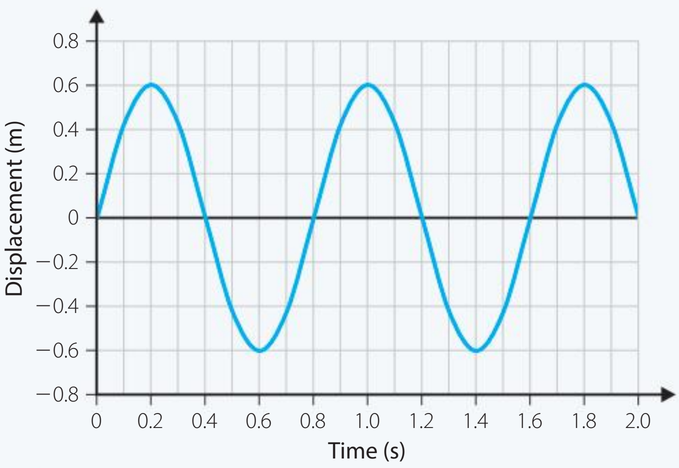

FIGURE 16.5.2 A displacement versus time graph of a mechanical wave

ANSWERS

a The amplitude is the maximum displacement of the crest:

$A = 0.6\,\text{m}$

b The period is the time for one full wave to be completed:

$T = 0.8\,\text{s}$

c Use the frequency equation:

$$f = \frac{1}{T}$$

Insert known values:

$$f = \frac{1}{0.8\,\text{s}}$$

Give the answer with the correct units and number of significant figures:

$f = 1.25\,\text{Hz}$

Displacement versus distance graph

wavelength (λ) the distance travelled by a wave before it repeats itself; units: m

wave velocity the velocity at which a wave crest moves through a medium

A displacement–distance graph shows the displacement of particles at different distances along the medium at a single instant in time. It can be very useful to calculate the amplitude, the wavelength and, together with the frequency, the wave velocity.

The **wavelength (λ)** is the distance that one wave covers before it repeats itself.

The **wave velocity** (v) is the speed at which the crests of the wave travel through the medium. Wave velocity must be differentiated from the velocity of the particles in the medium itself.

The wave velocity can be calculated from the wavelength and the period or the wavelength and the frequency, as below.

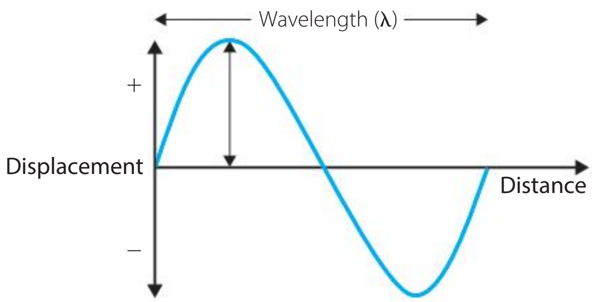

FIGURE 16.5.3 The displacement versus distance graph of a mechanical wave shows the displacement of all the particles of the medium experiencing a wave disturbance at an instant in time.

KEY FORMULA

$$v = \frac{\lambda}{T} = f\lambda$$

Where:

v = wave velocity ($m\,s^{-1}$)

λ = wavelength (m)

T = period (s)

f = frequency (Hz)

WORKED EXAMPLE 16.5.3

A wave on a string is measured as having a wavelength of 2.6 cm and a period of 0.30 s. Calculate the wave velocity.

ANSWER

Use wave velocity equation:

$$v = \frac{\lambda}{T}$$

Insert known values with the correct units:

$$v = \frac{0.026\text{ m}}{0.30\text{ s}}$$

Calculate the answer:

$v = 0.0866\,m\,s^{-1}$

Give the answer to the correct number of significant figures:

$v = 8.7 \times 10^{-2}\,m\,s^{-1}$

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WORKED EXAMPLE 16.5.4

Analyse the following graphs and calculate the velocity of the wave.

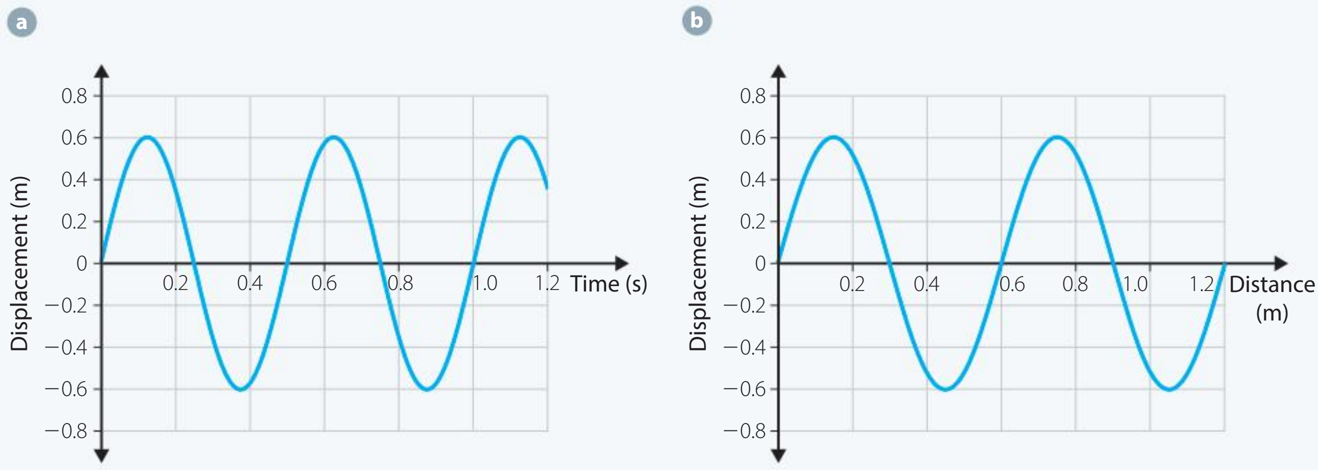

FIGURE 16.5.4 (**a**) Displacement vs time graph and (**b**) displacement vs distance graph

ANSWER

From graph a: $T = 0.5\,\text{s}$

From graph b: $\lambda = 0.6\,\text{m}$

Use wave velocity equation:

$$v = \frac{\lambda}{T}$$

Substitute the known values:

$$v = \frac{0.6\,\text{m}}{0.5\,\text{s}}$$

Give the answer to the correct number of significant figures:

$v = 1.2\,\text{m}\,\text{s}^{-1}$

Wave velocity in different media

Wave speed depends on the material and its state – solid, liquid or gas. Speed differences between materials in the same state are affected most by density. The greater the density of the material, the more sluggish will be the interactions between its neighbouring particles. This results in the wave travelling more slowly in denser materials. For example, a sound wave will travel nearly three times faster in helium than it will in air.

The speed of a sound wave in air depends on temperature and humidity. Temperature has the most effect because it affects density. Warm dry air is less dense than cold air. Humidity is also important. Moist air is less dense than dry air because water vapour is less dense than both oxygen and nitrogen.

The speed of a wave travelling in a wire also depends on how much the wire is being stretched – the tension in the wire. The greater the tension, the greater the speed of the wave.

It is important to note that the speed of a wave depends on the properties of the medium through which the wave is travelling, not the frequency or wavelength of the wave.

TABLE 16.5.1 The speed of sound in different media at 25°C and 1 atmosphere pressure

STATE	SUBSTANCE	SPEED ($m\,s^{-1}$)
Solids	Aluminium Nickel Steel Iron Brass Glass (flint)	6420 6040 5960 5950 4700 3980
Liquids	Water (sea) Water (distilled) Ethanol Methanol	1531 1498 1207 1103
Gases	Hydrogen Helium Air Oxygen Sulfur dioxide	1284 965 346 316 213

The wave velocity equation $v = \frac{\lambda}{T}$ is a reworking of the constant velocity formula of classical mechanics, $v = \frac{s}{t}$, with the wavelength taking the place of the displacement and the period taking the place of the time. Both equations can be used to calculate the wave velocity.

WORKED EXAMPLE 16.5.5

A wave has a frequency 10 Hz and a wavelength of 2.0 cm. How far will this wave travel in 1.5 minutes?

ANSWER

Use the constant velocity formula:

$$v = \frac{s}{t}$$

Rearrange for the required term, need to find s:

$s = vt$ (1)

Use the wave velocity equation:

$v = \lambda f$ (2)

Substitute equation 2 into equation 1:

$s = \lambda f t$

Substitute the known values:

$s = 0.2\,\text{m} \times 10\,\text{Hz} \times 90\,\text{s}$

Give the answer to the correct number of significant figures:

$s = 180\,\text{m}$

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TABLE 16.5.2 Wave terminology

TERM	DEFINITION	SYMBOL	UNIT
Displacement	Distance between the position and the mean position of a particle	s	metre (m)
Amplitude	The largest distance away from the mean position that a particle moves before returning	A	metre (m)
Frequency	The number of crests generated in a time interval	f	hertz (Hz)
Wavelength	The distance between successive crests	l	metre (m)
Period	The time it takes before a wave repeats itself	T	second (s)
Wave velocity	The rate at which a wave covers distance	v	metres per second (m s^{-1})

SECTION REVIEW 16.5

REMEMBERING

1 Define:
- **a** crest
- **b** trough
- **c** displacement
- **d** amplitude
- **e** period
- **f** frequency
- **g** wavelength
- **h** wave velocity.

2 What information can be obtained directly from a displacement–time graph?

3 What information can be found directly from a displacement–distance graph?

4 What can affect the speed of a wave?

UNDERSTANDING

5 Compare the terms 'displacement' and 'distance' as they are used in this section.

APPLYING

6 If a wave has a frequency of 23 Hz, calculate its period.

7 A slinky spring is oscillated at a rate of one pulse every 0.50 s, and it is found that the distance between crests is 0.60 m.
- **a** Calculate the wave velocity.
- **b** Calculate the frequency.
- **c** Draw a displacement vs time graph of the wave.
- **d** Draw a displacement vs distance graph for the wave.

8 A tsunami travels at 800 km h^{-1} across the ocean. It has a wavelength of 150 km. Calculate the time interval between wave crests.

ANALYSING

9 Analyse the graphs in Figure 16.5.5 to calculate the:

a amplitude
b period
c frequency
d wavelength
e wave velocity.

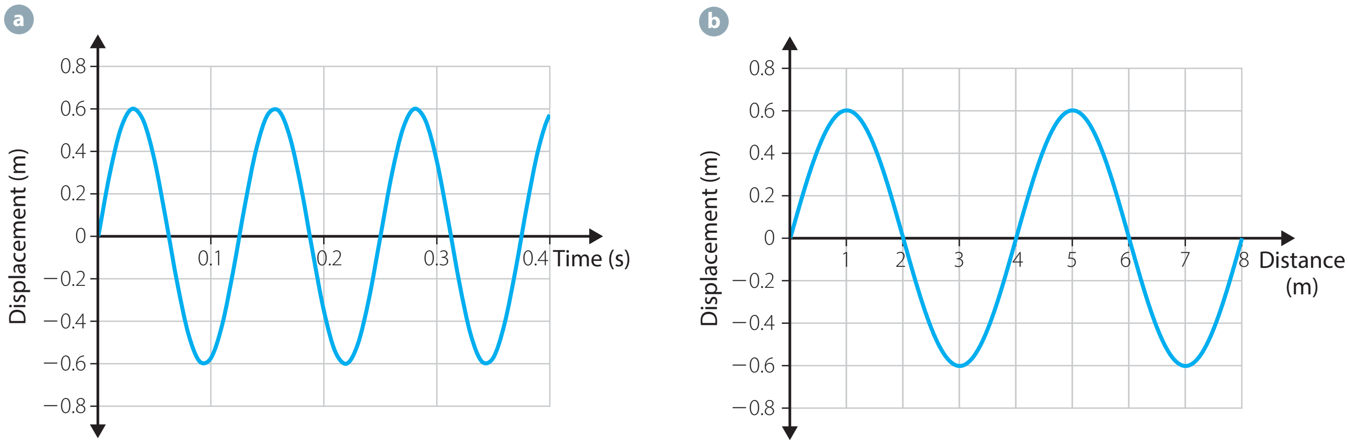

FIGURE 16.5.5

16.6 Reflection

16.6.1 Reflection

Waves can interact with surfaces, edges and interfaces between different materials. These interactions include reflection, refraction and diffraction. When a wave strikes a surface or a boundary between two media, a part of the wave will always be reflected. Evidence of this can readily be seen in echoes, which are reflections of sound waves, and the reflection of waves off the sea shore.

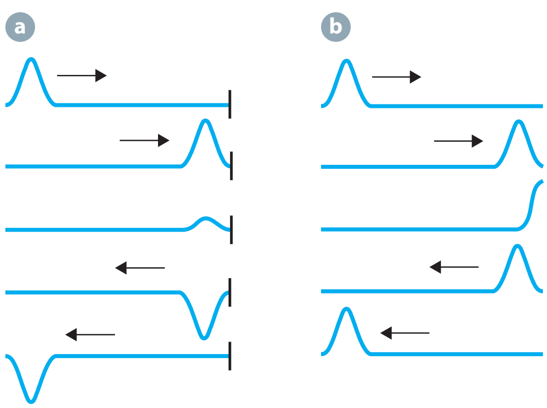

FIGURE 16.6.1
(**a**) A stretched string fixed at one end reflects waves (fixed-end reflection) upside down. The wavelength and frequency are unchanged.
(**b**) A stretched string free at one end reflects waves (free-end reflection) the same way up (in phase). The wavelength and frequency are unchanged.

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Reflection of transverse waves at a surface

When a wave pulse travels down a rope that is fixed at one end, a crest of a transverse wave is reflected as a trough (Figure 16.6.1(a)). When the rope is free at one end, a crest of a transverse wave is reflected as a crest (Figure 16.6.1(a)).

If a wave pulse travelling on a light string meets the boundary with a heavy string, part of the pulse is reflected and part is transmitted as shown in Figure 16.6.2. The part that is reflected will return in an inverted position as if it had struck a fixed boundary. The part that is transmitted into the heavier rope will remain upright. The heavier the second material, the less energy will be transmitted, and the more that will be reflected.

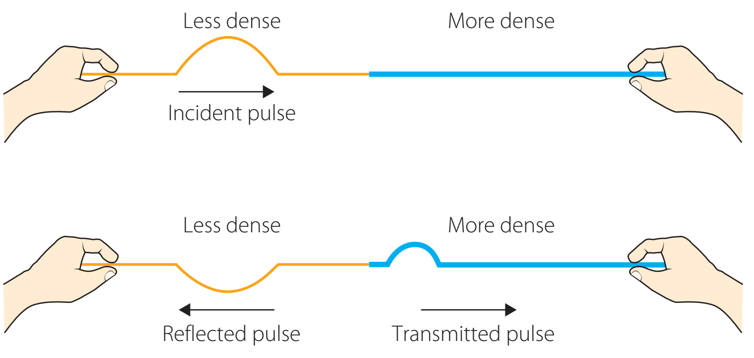


FIGURE 16.6.2 The transmission and reflection of a wave pulse at a boundary between two media of different densities

Reflection of two- or three-dimensional waves

When a two- or three-dimensional wave strikes a surface at an angle, the reflected wave bounces off the surface with an **angle of reflection** that is equal to the **angle of incidence**. This is known as the **law of reflection**.

The angle of incidence is defined as the angle that the **incident** (incoming) **wave** makes with a **normal** to the surface (that is, a line perpendicular to the surface) at the point of contact with the surface. The angle of reflection is the angle between the same normal and the reflected wave. Figure 16.6.3 gives a ray diagram of the law of reflection.

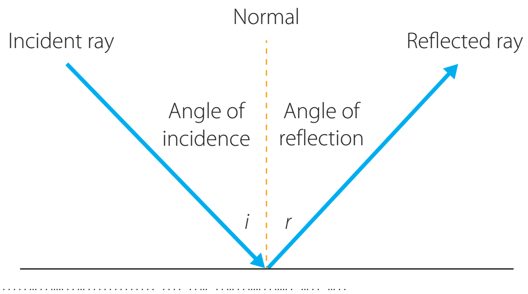


FIGURE 16.6.3 The law of reflection for waves states that the angle of incidence will equal the angle of reflection.

angle of reflection the angle made between a reflected wave and a normal drawn to the surface at the point of incidence

angle of incidence the angle made between an incident (incoming) wave and a normal drawn to the surface at the point of incidence

law of reflection when a wave is incident upon a surface, the angle of reflection is equal to the angle of incidence

incident wave incoming wave

normal a line drawn perpendicular to a surface

KEY FORMULA

Law of reflection

$\theta_i = \theta_r$

Where:

θ_i = angle of incidence

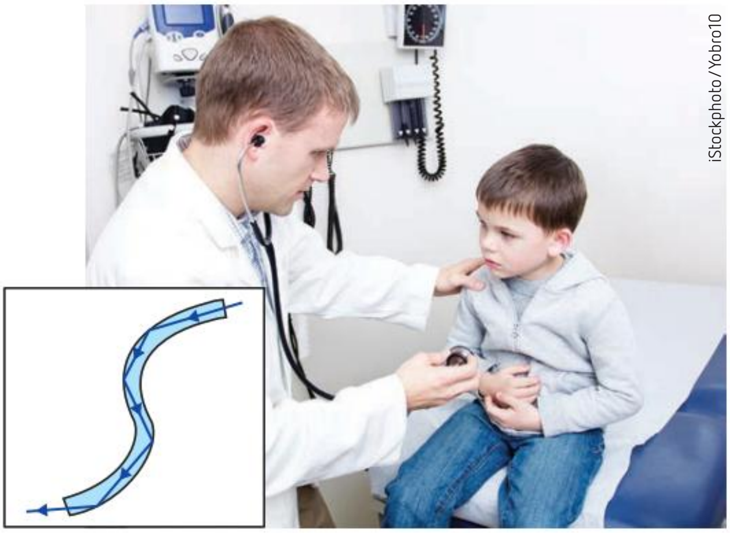
θ_r = angle of reflection

Total internal reflection

total internal reflection
the transport and containment of a wave by coherently reflecting it back and forth in a tube

Reflection of sound is used in stethoscopes and sonar depth sounders. In stethoscopes, sound waves reflect back and forth along the inner walls of a tube. This is known as **total internal reflection**.

FIGURE 16.6.4 Stethoscopes allow sound to travel to the ear by total internal reflection.



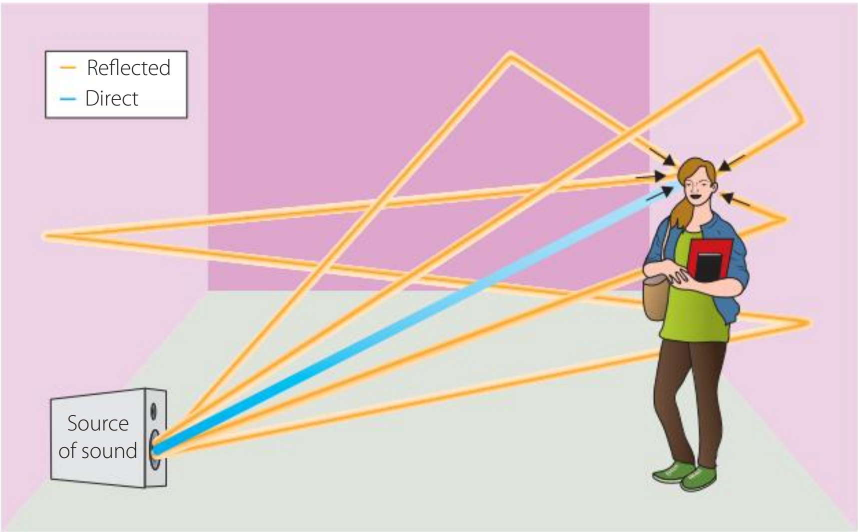
Reverberation

reverberation
the effect that occurs when too many sound wave reflections arrive at your ear for you to distinguish between the sounds

decay
the decrease in amplitude when the vibrating source of a wave is removed

When sound is produced in an enclosed space, a large number of echoes or **reverberations** build up and then slowly **decay** as the sound is absorbed by the walls and the air. When the sound source stops, the reflections continue, decreasing in amplitude, until they can no longer be heard. The longer the time of decay the greater the reverberation.

FIGURE 16.6.5 Multiple reflections and direct sound cause reverberation.



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Echoes

If you clap your hands or make a loud sharp sound at a distance from a good sound-reflecting surface, you hear an echo. The human ear can distinguish sounds that are about one-fifteenth of a second apart. In air, the speed of sound is about $340\,\text{m}\,\text{s}^{-1}$, so the minimum distance the sound must travel for you to hear the echo is:

$$v = \frac{\text{distance}}{\text{time}}$$

$$\text{distance} = v \times t$$

$$\text{distance} = 340\,\text{m}\,\text{s}^{-1} \times 6.67 \times 10^{-2}$$

$$\text{distance} = 22.7\,\text{m}$$

The minimum distance between the clap (source) and the echo surface is $\frac{22.7}{2} = 11.3\,\text{m}$.

SECTION REVIEW 16.6

REMEMBERING

1 Define 'reflection' as it applies to waves.

2 What happens to a pulse on a string with a fixed end when it is reflected?

3 What happens to a pulse on a string with a free end when it is reflected?

4 Describe what happens to a pulse on a string when it meets a junction with a string of higher density.

5 State the law of reflection as it applies to a two-dimensional wave.

UNDERSTANDING

6 Compare the phenomena of reverberation and echo an explain the differences and similarities between them.

7 Explain why it is useful that waves can travel in a tube such as a stethoscope.

APPLYING

8 For total internal reflection to be a useful way to transport waves, it is important that as much energy as possible is reflected back into the tube cavity and very little is transferred to the tube walls. Apply your understanding of wave reflection at a boundary between two media to suggest how this might be achieved.

9 The audience at a concert hall or auditorium wishes to hear as clear a sound as possible, free from echoes and with as little reverberation as possible. Make use of your understanding of wave reflection to suggest how this might be achieved.

16.7 Refraction

The **refraction** of waves involves a change in the direction of the waves as they pass from one medium to another. Refraction, or the bending of the path of a wave, is accompanied by changes in the speed and wavelength of the wave. This is due to the new medium having a different elastic property and/or mass density, which affects the rate of transmission of the wave energy. If the medium (or its properties) is changed, the speed of the wave is changed. The frequency does not change; therefore, from the wave velocity equation, the wavelength must change.

refraction the change in direction of a wave when it strikes a surface at an angle other than 90°. The speed and wavelength of the wave also change; frequency remains constant

16.7.1 Refraction

If a wave meets the interface at right angles it will not change direction, but its speed and wavelength will change. If it meets the interface at any other angle, its direction will also change, as shown in Figure 16.7.1 (a).

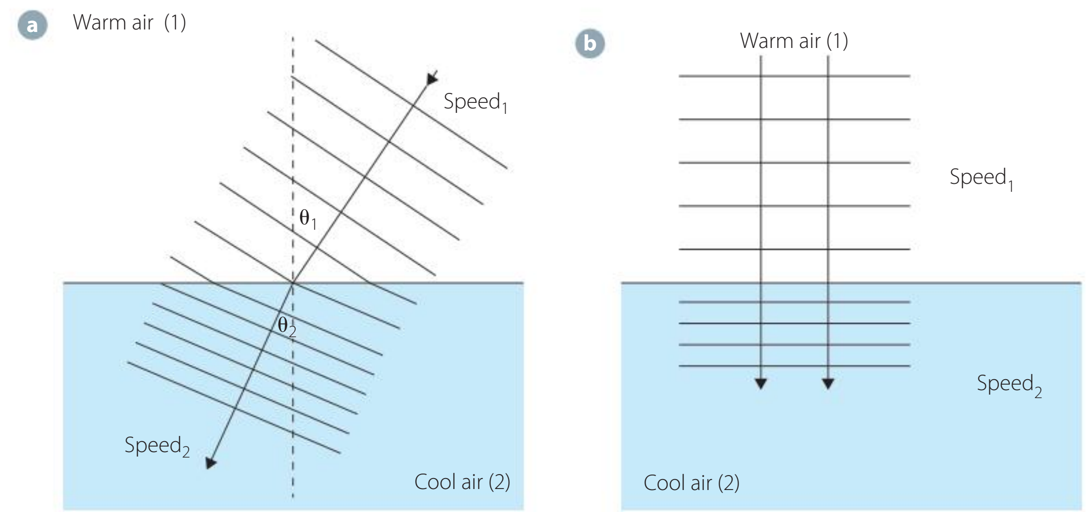

FIGURE 16.7.1 (**a**) A sound wave is refracted (changes direction) when it meets the boundary between two layers of different density at an angle other than a right angle. (**b**) At right angles there is no change in direction, but speed and wavelength both change.

The apparent position of underwater objects

Several optical illusions are caused by the refraction of light as it changes media, especially from water to air. As can be seen in Figure 16.7.2, the light rays travelling from the fish to the eye are refracted as they exit the water. As the human brain assumes that waves travel in straight lines, the observer believes the fish is at a position (its **apparent position**) which is higher than its actual position. Spear fishermen are aware of this phenomenon and know to aim lower than where the fish appears.

apparent position the position that an object appears to an observer, which may be different from its actual position due to the refraction of its light waves

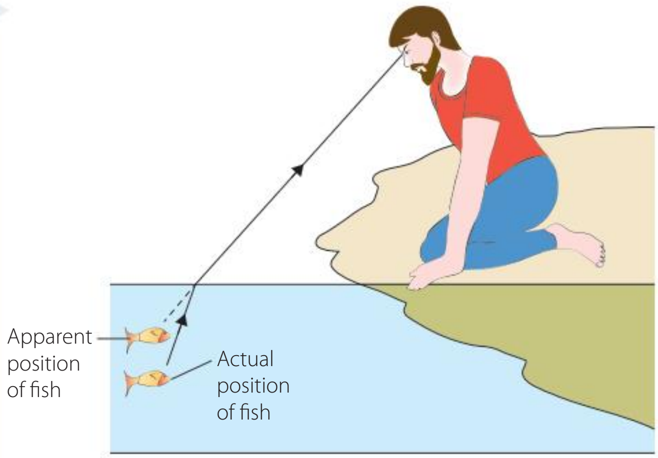

FIGURE 16.7.2 The apparent position of an underwater object is different from its actual position due to the refraction of light waves as they exit the water.

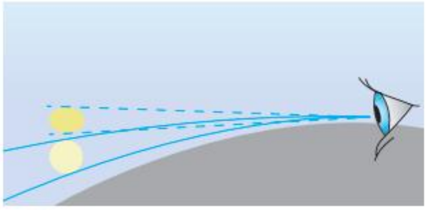

FIGURE 16.7.3 Incoming rays from the setting sun (solid lines) are refracted by the atmosphere and make it appear higher in the sky.

The setting sun

When the sun gets close to the horizon, the differing densities of the atmosphere cause refraction of the incoming light rays (Figure 16.7.3). This results in the apparent position of the sun appearing higher in the sky than its actual position. When the lowest edge of the sun appears to be just touching the horizon, the sun has actually already set!

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In addition, and as can also be seen in Figure 16.7.3, the incoming rays from the lower edge of the sun are refracted to a greater degree than the rays from the upper edge. This causes the characteristic oval shape of the sun at sunset. Because the Moon and stars all undergo the same phenomenon near the horizon, astronomical observations are always corrected for **atmospheric refraction**.

atmospheric refraction
the refraction of light rays as they pass through Earth's atmosphere

SECTION REVIEW 16.7

REMEMBERING

1 Define 'refraction' as it applies to waves.

2 Define 'apparent position'.

3 Define 'atmospheric refraction'.

UNDERSTANDING

4 Explain under what circumstance refraction of waves will occur.

5 Explain what happens to the wavelength, frequency, period and velocity of a wave as it moves into a denser medium.

6 Explain, with the use of a diagram, why the legs of a person standing in water up to their waist appear shorter to a person outside of the water than they would normally.

16.8 Diffraction

How is it that we can hear a sound even its source is around a corner ? Why is it that the sky is still light after the sun has set below the horizon? Both of these phenomena and many others can be explained by the concept of **diffraction**, which explains that when waves encounter an obstacle or a gap in a boundary, they will bend around it and move into the region behind it to some degree.

diffraction
the bending of waves around an obstacle

The amount of bending that occurs is dependent upon the wavelength of the incident wave and the size of the obstacle it encounters (Figure 16.8.1). The amount of spread is greatest when the wavelength is greater than the width of the obstacle or gap.

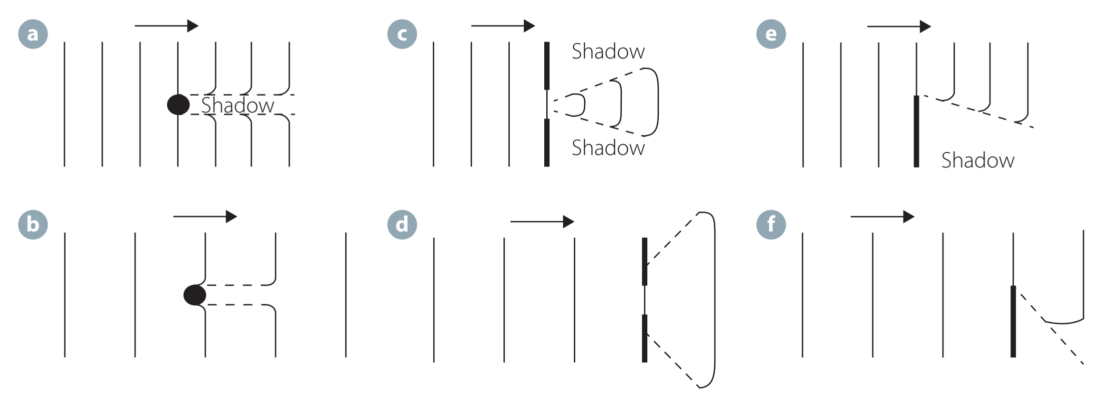


FIGURE 16.8.1 Diffraction of water waves: (**a**) short wavelength around an object, (**b**) long wavelength around an object, (**c**) short wavelength through a gap, (**d**) long wavelength through the same gap, (**e**) short wavelength around the edge of a barrier and (**f**) long wavelength around the edge of the same barrier.

Ocean waves at the entrance to a harbour

Diffraction is a very useful phenomenon when it comes to providing a safe harbour for boats. Many harbours and marinas are protected from the open ocean by an enclosing sea wall that contains a gap for the passage of vehicles.

The incoming waves diffract when they pass through the gap in the harbour wall and spread out as circular waves in the water of the harbour. In the process, the energy of the incoming section is dissipated into the whole of the circular wave and the amplitude will decrease. This effect is increased by decreasing the size of the gap and ensures the calmness of the harbour regardless of conditions in the open ocean.

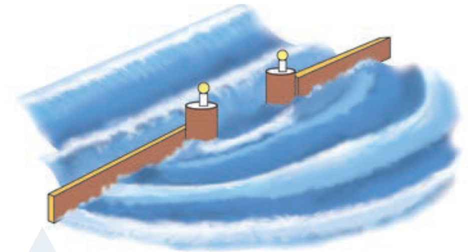


FIGURE 16.8.2 The diffraction of ocean waves at a gap in a harbour wall results in calmer waters.

SECTION REVIEW 16.8

REMEMBERING

1 Define 'diffraction' as it applies to the behaviour of waves.

2 Explain how the phenomenon of diffraction is used to create calm waters in a boat harbour.

UNDERSTANDING

3 Compare the properties of reflection, refraction and diffraction of waves.

4 Waves diffract around an obstacle. Suggest ways that the amount of diffraction that occurs can be increased.

APPLYING

5 Use the concept of diffraction of sound waves to explain why you would hear a loud whistle that is blown on the other side of a large tree trunk behind which you are hiding, if the tree is in an open field.

16.9 The principle of superposition

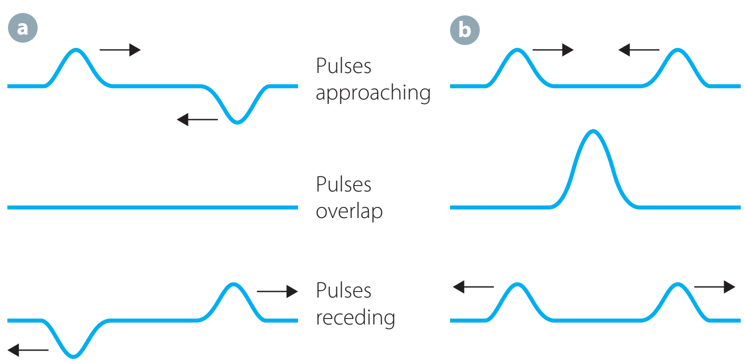
interference
wave overlap

out of phase
when the crests of a wave align with the troughs of another wave of equal wavelength

in phase
when two waves of equal wavelength have their crests and troughs aligned

If two waves of the same type (either longitudinal or transverse) are travelling through the same medium and are in the same place at the same time, **interference** or wave overlap will occur. Consider the two pulses shown in both images at the top of Figure 16.9.1 travelling towards each other. In each case, the pulses are of equal amplitude and velocity, but in Figure 16.9.1(a) the pulses are **out of phase** (one is a crest and the other a trough) and in Figure 16.9.1(b) the pulses are **in phase** (both are crests).

FIGURE 16.9.1 Two wave pulses approaching each other on a string. When they meet they interfere (**a**) destructively, (**b**) constructively.



Even though in both cases shown in Figure 16.9.1 the pulses meet and pass through each other, in Figure 16.9.1(a) the interference region has an amplitude of zero, while in Figure 16.9.1(b) the interference region has an amplitude equal to twice the amplitude of a single pulse. This is the basis of the **principle of superposition**, which states that when two or more waves of the same nature travel past a point in a medium, the medium will undergo a resultant displacement at that point. The resultant displacement of the medium at that point is the sum of the individual particle displacements due to the waves at that point.

In Figure 16.9.1(a), the waves are out of phase and therefore have opposite displacements at the instant they interfere with each other. Because of superposition, the resultant wave will have a displacement of zero. This is called **destructive interference**. Conversely, in Figure 16.9.1(b), the waves are in phase and, as such, the sum of the displacements makes a total greater than the displacement of either of the individual pulses. This is called **constructive interference**.

principle of superposition when two or more waves of the same nature travel past a point in a medium, the medium will undergo a resultant displacement at that point, which is the sum of the individual particle displacements due to the waves at that point

destructive interference the interference of out-of-phase waves resulting in a decreased displacement at the point of overlap

constructive interference the interference of in-phase waves resulting in an increased displacement at the point of overlap

Doppler effect the shift in the wavelength and frequency of waves that results from the relative motion of the source and the receiver

The Doppler effect and the sonic boom

When a source of waves, for example a siren, is approaching a receiver, the pitch heard is greater than that emitted. This is because each wave is emitted a little closer to the observer than the previous wave. The reverse effect (i.e., a sound with lowered pitch) is heard when the source moves away from the receiver. This is known as the **Doppler effect**. It is the relative motion of source and receiver that changes the wavelength of the sound received relative to the sound emitted. The number of sound waves received per second, the frequency, depends on the relative speed of source and receiver.

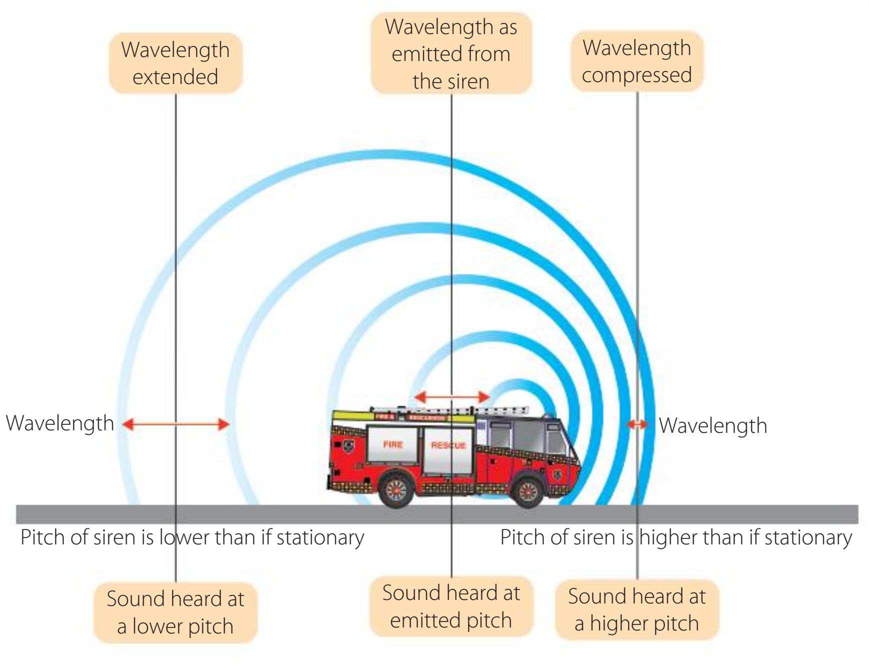


FIGURE 16.9.2 The Doppler effect for a fire engine siren. The wavelength of sound waves is compressed or extended due to the relative motion of the source and the receiver.

FIGURE 16.9.3 A jet fighter plane just breaking the sound barrier and forming a typical condensation cloud as the shockwave forms.

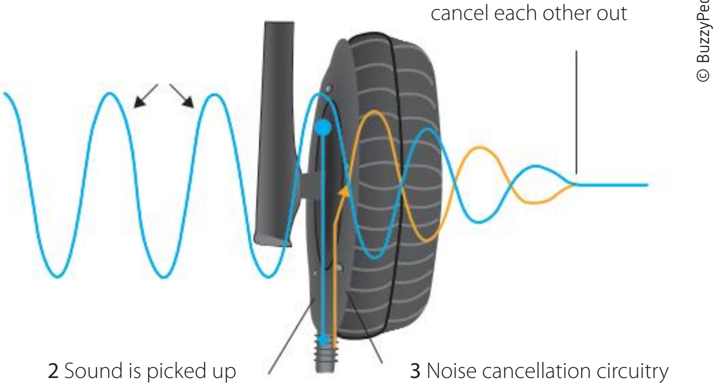
When a plane flies through the air, it creates a series of sound waves in front of it and behind it. These waves travel at the speed of sound. As the speed of the plane increases, the waves are forced closer together, and the principle of superposition applies. The sound waves merge into a single shockwave at the speed of sound. At 'supersonic' speeds, the plane begins pushing the air like a plough. This high-pressure shockwave sounds like a boom (hence the name sonic boom), and is continuous along what is called the boom carpet for the entire supersonic flight. Low-pressure rarefactions cause rapid condensation, and hence clouds to form, around the plane.

Noise-cancelling earphones

16.9.1 Superposition of waves

A clever use of sound interference is to cancel noise. Headphones designed to cancel noise with destructive interference create a sound wave that is the exact opposite of the incoming sound. The headphones use a microphone to receive the sound waves and with real-time fast electronics produce a sound wave that is the exact reverse of the incoming signal. This new signal interferes with the original signal, as shown in Figure 16.9.4.

FIGURE 16.9.4 Noise-cancelling headphones work by creating a sound wave that is the exact opposite of the incoming sound.



SECTION REVIEW 16.9

REMEMBERING

1 Define:

a interference

b constructive interference

c destructive interference.

2 Recall the conditions that are necessary for two wave pulses to be considered out of phase or in phase with each other.

UNDERSTANDING

3 Explain the principle of superposition in your own words.

4 Explain why the siren of a fire engine increases in frequency when the fire engine begins moving towards you and decreases in frequency when it passes you.

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APPLYING

5 Two wave pulses of equal frequency and wavelength are in phase as they travel towards each other on a rope. Calculate the maximum amplitude of the wave that results when they meet. One wave has an amplitude of 6.0 cm and the other has an amplitude of 9.0 cm.

6 Two wave pulses of equal frequency and wavelength are out of phase as they travel towards each other on a rope. Calculate the maximum amplitude of the wave that results when they meet. One wave has an amplitude of 6.0 cm and the other has an amplitude of 9.0 cm.

7 Using Figure 16.9.3 as a guide, illustrate the wavefronts for sound waves that are emanating from the front of a plane travelling at the speed of sound.

16.10 Standing waves

A **standing wave**, or **stationary wave**, is a wave that does not appear to be moving. If you shake waves onto a string that is fixed at the other end, the forwards and reflected waves will interfere. Usually, the effect is messy. But if you get it just right, a fixed pattern of maximum and minimum displacement will appear.

A standing wave (Figure 16.10.1) is created when two waves of the same frequency and amplitude but travelling in opposite directions exist in a medium.

standing wave (stationary wave)
a wave that oscillates in place, without transmitting energy along its extent. Standing waves have stable points called nodes, where there is no oscillation

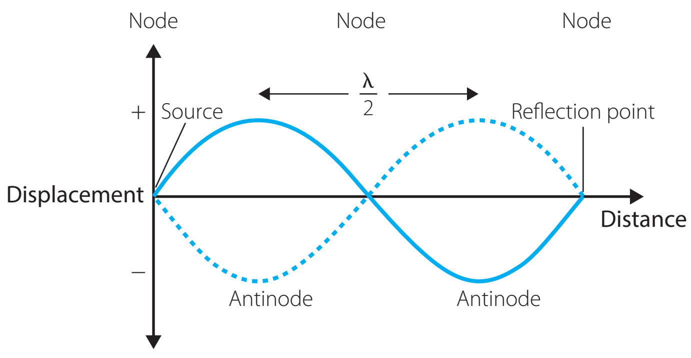

FIGURE 16.10.1 A standing wave in a stretched string fixed at both ends showing the nodes and antinodes. The solid line represents the string's displacement at an instant in time and the dotted line the string's displacement half a period $\left(\frac{T}{2}\right)$ later.

The **nodes** are points where destructive interference always occurs. At these points, at any moment in time, the amplitudes of the two waves are always the same magnitude but in opposite directions. Hence, when the crest of one wave passes through this point, a trough of the same size is also passing through. When the displacement due to one wave is half the amplitude, the displacement due to the other wave is also half the amplitude, but in the opposite direction, and so on. Whatever the displacement due to one wave, the displacement due to the other is the same size but the opposite direction. Superposition means that these two displacements add to give zero total displacement at any time at a node, hence a particle at a node does not move.

node
point along a standing wave at which the amplitude is zero; it is the result of a crest overlapping a trough

At the **antinodes**, the particles move up and down constantly and reach the maximum displacement possible. The maximum displacement occurs when two crests (or two troughs) meet at this point to give a displacement twice that of the amplitude of the individual waves. So, at an antinode the particles oscillate up and down between displacements of $^{-}2A$ and $2A$. The frequency with which they move up and down is the same as the wave frequency.

In between nodes and antinodes, the particles oscillate up and down with the same frequency, but with smaller amplitudes, to produce the pattern shown in Figure 16.10.1.

antinode
point along a standing wave at which the wave has maximum amplitude; it is the result of a crest overlapping a crest or a trough overlapping a trough

Standing wave patterns are always characterised by an alternating pattern of nodes and antinodes. The distance between nodes or between antinodes along the string or spring is half a wavelength, $\frac{\lambda}{2}$.

Musical instruments

The great majority of acoustic instruments rely on the creation of standing waves to produce their unique tones. This may be vibrating strings in the case of stringed instruments such as the guitar, harp or piano, moving air inside a column of air such as occurs in a flute, saxophone or organ pipe, or the vibration of a membrane or solid object as used in percussion instruments.

Figure 16.10.2 clearly shows the standing waves that occur in the strings of a harp. Note that each string has a different wavelength and therefore frequency, and it is this fact that gives each string a different tone.

FIGURE 16.10.2 Each string on a harp has a unique standing wave frequency and as such emits a unique tone.

SECTION REVIEW 16.10

REMEMBERING

1 Define 'standing wave'.

2 What is the difference between a node and an antinode?

3 What is the distance between a node and an antinode?

UNDERSTANDING

4 Match the terms in the first column of the table below with the conditions in the second column that describe what is causing them.

Node	Constructive interference
Antinode	Destructive interference

5 Explain why each string of a piano has a unique frequency.

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CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 Define the following terms.

a Intensity
b Amplitude
c Wave front
d Period
e Frequency
f Wavelength
g Wave velocity
h Mechanical wave
i Transverse wave
j Longitudinal wave
k Compression
l Rarefaction
m Seismic focus
n Epicentre
o Body wave
p S wave
q P wave
r Seismograph

2 Explain how the intensity of a wave decreases with distance from the source.

3 Explain the principle of superposition.

CATEGORY QUESTIONS

4 Name the body wave that is an example of a:

a longitudinal wave
b transverse wave.

5 Compare the mechanics and propagation of the two types of body waves.

6 Describe factors that may impact on the intensity of a seismic wave as felt on the surface of Earth.

7 Describe what might impact on the speed at which a body wave will propagate through Earth.

ELABORATION QUESTIONS

8 Research how recordings of seismic wave patterns can be used to calculate the position of the seismic focus and give an insight into the internal structure of Earth.

9 Suggest how the development of the tectonic plate model helped to clarify the cause of seismic waves.

10 Suggest ways in which the humanitarian and economic impact of seismic waves could be reduced.

EVIDENCE QUESTIONS

11 Identify the sources used to explain how seismic waves can be used to calculate the position of the seismic focus and give an insight into the internal structure of Earth.

12 Explain how the existence of seismic waves helped with the development of the tectonic plate model.

13 What other evidence gives support to the tectonic plate model?

END-OF-CHAPTER EXAM

End-of-chapter test

1 The intensity of a wave is defined as a measure of:

A the energy of the wave.

B the power of a wave.

C the rate at which the energy of a wave is travelling through a given area.

D the rate at which the power of a wave is travelling through a given area.

2 The direction of the particle motion in a medium containing a longitudinal wave is:

A parallel to the velocity of the wave.

B perpendicular to the velocity of the wave.

C at an acute angle to the velocity of the wave.

D at an obtuse angle to the velocity of the wave.

3 Which of the following wave features cannot be deduced from a displacement–time graph of a wave?

A Period

B Amplitude

C Frequency

D Wavelength

4 If a wave pulse travelling on a light string is incident upon the boundary with a heavy string, then the reflected wave pulse will be:

A upright and diminished.

B upright and amplified.

C inverted and diminished.

D inverted and amplified.

5 Which of the angles in Figure 16.11.1 is representative of the angle of reflection?

A a

B b

C c

D d

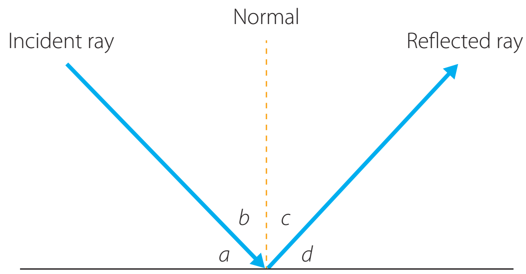

FIGURE 16.11.1

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6 The distance between adjacent nodes in a standing wave on a string is equal to:

A $\frac{1}{4}$ wavelength.

B $\frac{1}{2}$ wavelength.

C 1 wavelength.

D 2 wavelengths.

7 When two in-phase wave pulses meet at a point, their interaction results in:

A constructive interference.

B destructive interference.

C a standing wave.

D total internal reflection.

8 What is the name given to the bending of a wave around an object?

9 What is the name given to the bending of a wave as it changes medium?

10 What is the name given to the point on a standing wave with maximum displacement?

11 Compare the motion of a transverse wave with the motion of a particle in the medium through which the wave is travelling.

12 Compare a seismic S wave to a seismic P wave.

13 State the principle of superposition.

14 A surfer notices that wave crests are passing underneath his board every 5.0 s. If he measures the distance between each wave to be 5.5 m, how fast are the waves travelling?

15 If a sound wave in air has a frequency of 215 Hz and is travelling with a speed of 343 m s^{-1}, how far apart are the compressions?

16 Explain the mechanics of sound waves and how they interact with the ear to produce the sensation of sound.

17 Explain why the speed of waves changes in different media.

18 Explain the formation of standing waves.

19 Calculate the distance travelled in 3.0 s by a 2400 Hz sound wave that has a wavelength of 14.3 cm.

20 Analyse the following displacement–time graph and displacement–distance graph of the same wave to calculate the wave's:

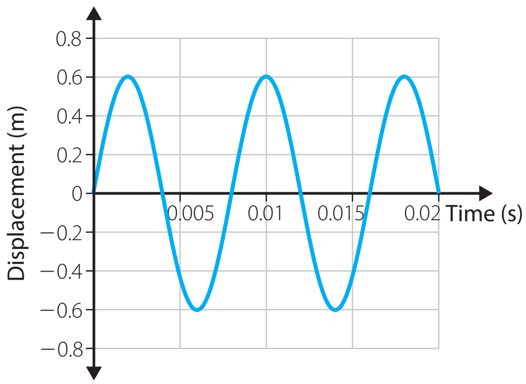
a amplitude.

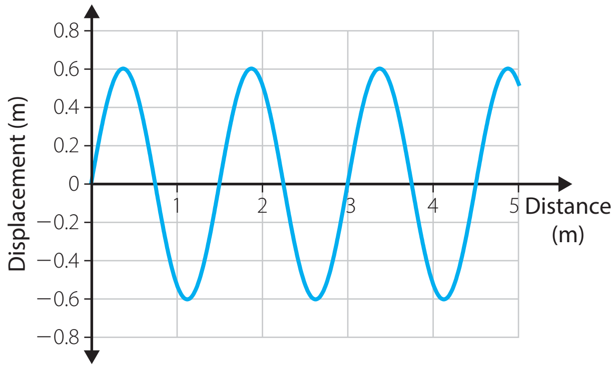
b period.

c frequency.

d wavelength.

e velocity.





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17 SOUND

Introduction

We saw in the previous chapter that if the frequency of a repeated disturbance is just right, then a standing wave can be produced on a string. These standing waves are the source of the tones emitted by all stringed instruments. The fundamental concepts behind their formation can be extended to included vibrating air within a column or tube.

In this chapter, we will investigate the mechanics of standing wave production and examine the characteristic frequencies that result in a sound being produced by a string and in an air column.

Stimulus questions

How do objects produce sound?

How can one vibrating object cause another object to vibrate?

How do stringed instruments and wind instruments produce sound?

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17.1 Resonance

Natural vibrations

natural (or free) frequency
the vibration frequency that occurs when an object is displaced from its equilibrium position and then left to vibrate by itself

The **natural (or free) frequency** of an object is the frequency with which the object will vibrate if it is displaced from its equilibrium position and then left to vibrate by itself.

When a tuning fork is struck, the prongs vibrate about their mean position (Figure 17.1.1). Elastic restoring forces pull the prongs back towards their equilibrium position and momentum combines to drive the prongs back and forth. The tuning fork vibrates at its natural frequency. This phenomenon can be observed in guitar strings, organ pipes, wind instruments, drums, pendulums and masses hanging on the end of springs (think bungee jumping!) – all have natural frequencies.

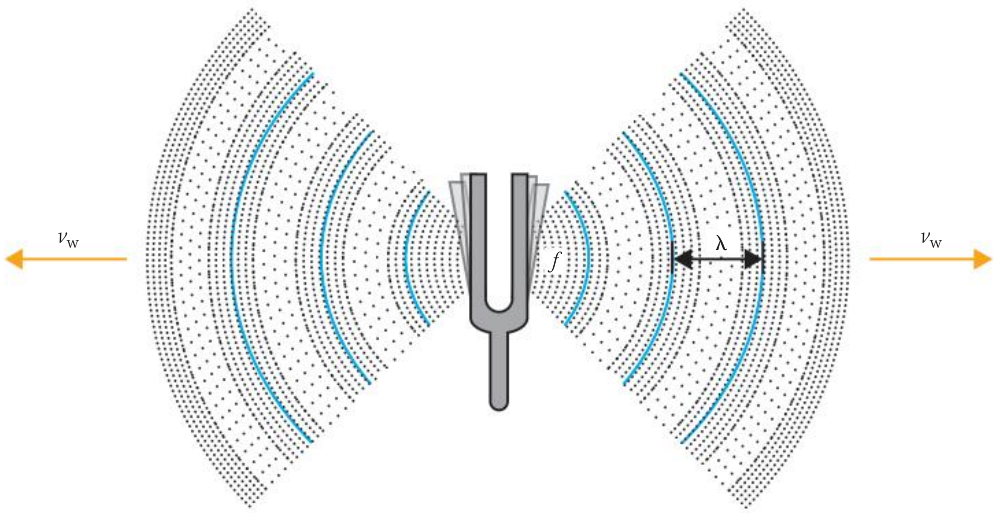

FIGURE 17.1.1 Sound waves produced from the freely vibrating tuning fork with a frequency f, speed v_w and wavelength λ.

The frequency (and period) of vibration is determined by the properties of the vibrating object. For example, a plucked guitar string vibrates at different natural frequencies depending on its length, mass per unit length and the tension in the string.

The only energy driving a free vibration is the initial energy; thus, in time these vibrations die away because of friction – energy transfers to the surroundings. For example, the tuning fork is repeatedly colliding with air molecules, leading to a momentum exchange. The tuning fork loses energy progressively while the kinetic energy of the air molecules that come in to contact with the fork is increased, until eventually, the tuning fork comes to rest.

Forced vibrations

forced vibration
the vibration that occurs in an object when it is forced to vibrate by another vibrating object

A **forced vibration** occurs when one vibrating object makes another object vibrate. If a vibrating tuning fork is struck on a rubber stopper, it emits a low-intensity sound that can be heard only with difficulty. However, if the same vibrating tuning fork is held with its shaft on a wooden bench or tabletop, the sound is heard throughout a classroom.

The sound is louder when the fork is in contact with the bench because the fork causes the bench to vibrate with the same frequency. The benchtop has a larger vibrating area than the tuning fork. Consequently, these forced vibrations disturb a greater volume of air and produce a louder sound.

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Resonance

If a person blows across the mouth of a bottle (Figure 17.1.2), the air in the bottle is made to vibrate and a note will be heard. The frequency of this note is determined by the dimensions of the bottle. The sound results from the free vibrations of the air in the bottle.

When a person purses their lips and blows through them, the sound of the rushing air can be heard. This sound is made up of waves of very many different frequencies. This sort of sound is called 'white noise' in analogy to 'white light', which is composed of many frequencies of light.

When a person blows air across the top of a bottle, they are providing waves of many different frequencies to the air column inside the bottle. Most of these waves transfer energy very inefficiently to the air column. But waves of one particular frequency, the natural or **resonance** frequency, transfer energy very efficiently and set up a standing wave in the bottle. The frequency of this standing wave is the frequency of the note you hear. Resonance will only occur when the driving frequency matches the natural frequency and, as a result, the amplitude of vibration of the resonating object will increase dramatically.

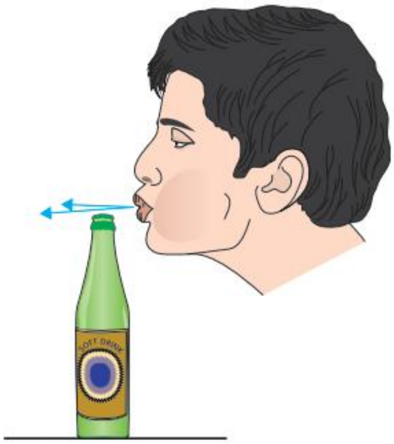


FIGURE 17.1.2 Blowing across an open bottle results in the air inside being made to vibrate and, in turn, causes a note to be emitted.

This is how woodwind instruments work; the musician makes a particular mouth shape, called the *embouchure*, and blows air through their lips over a reed. The reed vibrates with the many frequencies of the waves produced by the blowing. The wave of just the right frequency then creates a standing wave in the pipe of the instrument. In effect, the body of the instrument selects and amplifies one particular frequency from many. By covering different holes, the musician determines which frequency (which note) is selected. Brass instruments work in the same way, but the musician's vibrating lips do the job of the reed.

resonance
when an object is made to oscillate at its natural frequency by the vibration of another object that is also vibrating at that natural frequency

If a tuning fork is held over the mouth of the bottle and the frequency of the tuning fork (the **driving frequency**) differs from the natural frequency of the air column, only a feeble sound is heard. The frequency of this feeble sound is the same as the frequency of the fork and is due to the forced vibrations in the air column in the bottle.

driving frequency
the vibration of an object that causes a second object to undergo resonance

When a tuning fork vibrating at the same natural frequency as the air column in the bottle is held over the mouth of the bottle, the sound intensity is increased considerably. The energy of the vibration across the top of the bottle is transferred very efficiently to the vibrating air column inside the bottle.

In these examples, a standing wave or resonance is produced when the frequency of the forced vibration coincides with the natural frequency of the system. Resonance can occur when the driving frequency coincides with any of the standing waves of the resonating object. The frequencies that are produced as a result are called **resonant frequencies**. When an object is resonating, energy is being transferred with maximum efficiency from the driving oscillator to the receiving oscillator.

resonant frequencies
the possible standing wave frequencies of an object

Figure 17.1.3 shows forced vibrations when two tuning forks are mounted on sounding boxes. The length of the sounding box should be one quarter of the wavelength of the sound wave produced when the tuning fork vibrates.

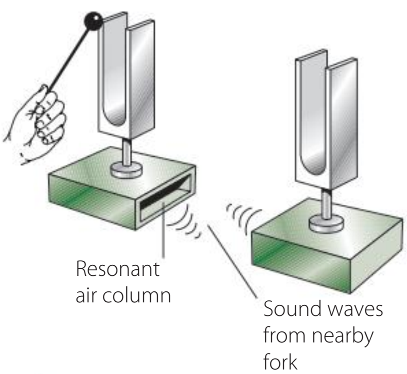


FIGURE 17.1.3 Energy supplied to one tuning fork forces the other to resonate.

Note the following points about resonance:

- Resonance will only occur when the driving frequency matches the natural frequency.
- The amplitude of the vibration of the resonating object will increase dramatically.
- When an object is resonating, energy is being transferred with maximum efficiency from the driving oscillator to the receiving oscillator.

17.1.1 Resonance

The destruction of the Tacoma Narrows Bridge due to the formation of a standing wave along its structure.

SECTION REVIEW 17.1

REMEMBERING

1 Define:

- **a** natural frequency
- **b** forced vibration
- **c** resonance.

2 Describe the difference between a natural vibration and a forced vibration.

3 Describe the difference between the driving frequency and the resonant frequency of a resonating system.

4 Explain how blowing across the top of a bottle can produce a loud, clear note.

UNDERSTANDING

5 What conditions are required for resonance to occur?

6 The vibrating air in the bottle in Figure 17.1.2 is called a standing wave. Explain why it is called a standing wave.

APPLYING

7 Explain how you could use a tuning fork to force another tuning fork to vibrate at its natural frequency.

8 Use the concept of resonance to explain how a glass can be shattered if the right frequency of sound is played loudly in its vicinity.

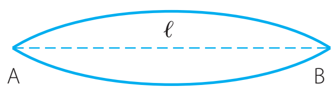
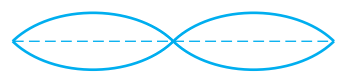
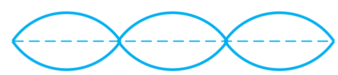
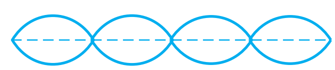
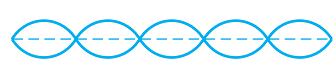
17.2 Vibrating strings

The formation of a standing wave in a fixed string is only one such possible pattern; every object has more than one possible standing wave pattern.

vibration mode or harmonic
standing wave pattern

Figure 17.2.1 shows possible **vibration modes**, or **harmonics**, for stationary waves on a string or wire fixed at both ends. There is a node at each fixed end for all modes of vibrations.

FIGURE 17.2.1 The first five harmonics of a string fixed at both ends

Vibration mode	Wave pattern	f and λ
Fundamental mode of vibration 1st harmonic		$\lambda_1 = 2\ell$ $f_1 = \frac{v}{2\ell}$
2nd harmonic		$\lambda_2 = \ell$ $f_2 = 2f_1$
3rd harmonic		$\lambda_3 = \frac{2}{3}\ell$ $f_3 = 3f_1$
4th harmonic		$\lambda_4 = \frac{1}{2}\ell$ $f_4 = 4f_1$
5th harmonic		$\lambda_5 = \frac{2}{5}\ell$ $f_5 = 5f_1$

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The fundamental mode of vibration is also referred to as the **first harmonic**. Wires and strings of musical instruments can be made to vibrate at frequencies other than their fundamental frequency. These higher modes of vibration are notes or tones of higher frequency than the fundamental or natural frequency (and are of smaller amplitude). The second mode of vibration harmonic is the called the second harmonic; the third mode of vibration is called the third harmonic, and so on.

first harmonic the simplest mode of vibration that accounts for the fundamental tone

The frequency of each harmonic is its harmonic number times the fundamental frequency. If the fundamental frequency of a stretched string is 40 Hz, the fourth harmonic has a frequency of $4 \times 40 = 160$ Hz.

The fundamental mode of vibration (the first harmonic) is generated when the stretched string is plucked in the middle. If you look at the fundamental vibration mode in Figure 17.2.1, the pattern represents half a wave, so its wavelength, λ_1, is twice the length of the string: $\ell = \frac{\lambda_1}{2}$.

The second harmonic is generated when the stretched string is plucked a quarter of the way along the string. The second harmonic mode in Figure 17.2.1 shows that the pattern represents a complete wave, so the wavelength of the second harmonic, λ_2, is equal to the length of the string: $\ell = \lambda_2$.

The third harmonic is generated when the stretched string is plucked a sixth of the way along the string. The pattern of the third vibrational mode in Figure 17.2.1 represents one and a half complete waves, so the wavelength of the third harmonic, λ_3, is equal to two-thirds the length of the string: $\ell = \frac{3\lambda_3}{2}$.

For strings attached at both ends to be resonating, the length of the string is related to the resonating wavelength by the relationship:

$$\ell = n\frac{\lambda_n}{2}$$

Putting this together with $v = f\lambda$, where v is the speed of the travelling wave in the string, the following relationships become apparent.

- The fundamental or first mode has frequency $f_1 = \frac{v}{\lambda_1} = \frac{v}{2\ell}$.
- The second harmonic has frequency $f_2 = \frac{v}{\lambda_2} = \frac{v}{\ell} = 2f_1$.
- To generalise, the nth harmonic has frequency $f_n = \frac{v}{\lambda_n} = n\frac{v}{2\ell} = nf_1$.

KEY FORMULA

Relationship between the length of a string and its resonant frequencies

$\ell = n\frac{\lambda_n}{2}$

Where:

ℓ = length of the string

n = mode or harmonic number ($n = 1, 2, 3 \ldots$)

λ_n = wavelength of the nth mode or harmonic

KEY FORMULA

The frequency of resonant frequencies on a string

$f_n = \frac{v}{\lambda_n} = n\frac{v}{2\ell} = nf_1$

Where:

f_n = the frequency of the nth mode or harmonic

ℓ = the length of the string

n = the mode or harmonic number ($n = 1, 2, 3 \ldots$)

λ_n = wavelength of the nth mode or harmonic

f_1 = the fundamental frequency

v = the wave velocity

WORKED EXAMPLE 17.2.1

The fundamental frequency of a string 2.4 m long and fixed at both ends is 22 Hz.

a What are the frequencies of the next three harmonics?

b Is it possible to produce stationary waves of frequency 50 Hz in this string?

c What is the speed of the waves in the string?

d What is the wavelength of the first harmonic?

ANSWERS

a The frequency of each harmonic is its harmonic number times the fundamental frequency.

i $2 \times 22\,\text{Hz} = 44\,\text{Hz}$

ii $3 \times 22\,\text{Hz} = 66\,\text{Hz}$

iii $4 \times 22\,\text{Hz} = 88\,\text{Hz}$

b As 50 Hz is not the frequency of one of the harmonics of this string (a whole number multiple of the fundamental frequency), it is not possible to produce stationary waves of this frequency with the string under the same tension.

c Apply the equation:

$$f_n = n\frac{v}{2\ell}$$

Rearrange to make the unknown the subject:

$v = f_n n 2\ell$

Insert known values:

$v = 22\,\text{Hz} \times 1 \times 2 \times 2.4\,\text{m}$

Calculate the answer:

$v = 105.6\,\text{m s}^{-1}$

Give the answer to the correct number of significant figures:

$v = 110\,\text{m s}^{-1}$

d Apply the equation:

$$\ell = n\frac{\lambda_n}{2}$$

Rearrange to make the unknown the subject:

$$\lambda_n = \frac{2\ell}{n}$$

Insert known values:

$\lambda_1 = 2 \times 1 \times 2.4\,\text{m}$

Calculate the answer with the correct number of significant figures:

$\lambda_1 = 4.8\,\text{m}$

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SECTION REVIEW 17.2

REMEMBERING

1 What is the difference between the fundamental mode and the second mode of vibration in a string?

UNDERSTANDING

2 A standing wave in a spring results from the interference between an incident wave and its reflection. The two waves cancel at the nodes.

Does this mean that energy is destroyed? Explain your answer.

3 Two component waves producing a standing wave pattern each have a wavelength of ℓ. Identify the distance between:

- **a** adjacent nodes
- **b** adjacent antinodes
- **c** a node and the closest antinode.

4 Which pattern(s) in Figure 17.2.2 could represent a standing wave pattern on a string of length ℓ fixed at both ends?

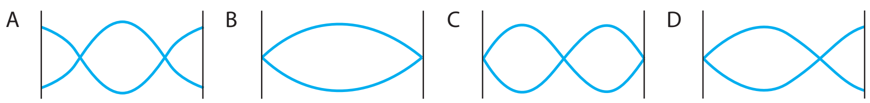

FIGURE 17.2.2

APPLYING

5 The apparatus used to investigate the vibrations of a stretched string or vibrating wire is called a sonometer or monochord (Figure 17.2.3).

The stretched wire on a monochord is 0.80 m long.

- **a** What is the wavelength of the fundamental mode of vibration?
- **b** If the speed of the wave travelling in the wire is 200 m s^{-1}, what is the fundamental frequency?
- **c** If the vibrating length of the wire is shortened, does the fundamental frequency increase or decrease? Give a reason for your answer.
- **d** If you added more slotted masses to the sonometer, the frequency of the note it produces will increase. Why is this?

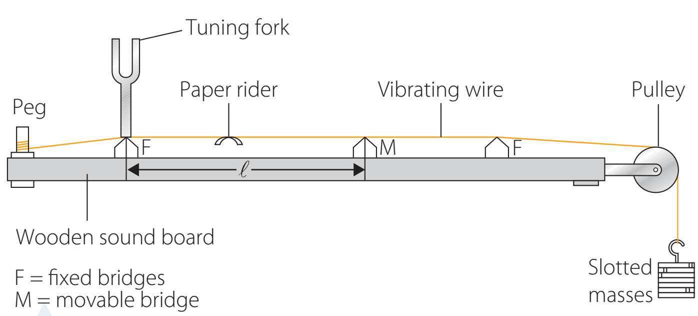

FIGURE 17.2.3

ANALYSING

6 What is the longest wavelength of a standing wave that can be created on a string stretched between fixed supports 12 cm apart?

7 Two successive harmonics of a vibrating string are 300 Hz and 360 Hz. What is the fundamental frequency of the string?

17.3 Air columns

Longitudinal stationary sound waves can be created in both open and closed pipes, such as is the case in woodwind, pipe organ and brass instruments (Figure 17.3.1).

open pipe
a pipe that is open at both ends

closed pipe
a pipe that is open at one end and closed at the other end

Resonance occurs when sound waves match one of the harmonic wavelengths of the pipe. **Open pipes** are pipes that are open at both ends and **closed pipes** are open at only one end. Resonance in air columns is related to the length of the pipe and the speed of sound in air, which is temperature dependent.

Reflection of sound waves in pipes

Waves confined in pipes travel as plane waves, not spherical waves as they do in the open air. As a compression travels along the pipe it continually reflects off the walls of the pipe. This maintains the compression. When the compression reaches the end of an open pipe it is no longer confined and rapidly expands into the air, leaving behind a rarefaction that travels back down the pipe. The compression has been reflected as a rarefaction. This is similar to a fixed-end reflection in strings and springs.

When a rarefaction travels along the pipe it continually reflects off the walls of the pipe. This maintains the rarefaction. When the rarefaction reaches the end of an open pipe, the higher-pressure air outside the pipe rapidly expands into the rarefaction creating a compression that travels back down the pipe. The rarefaction has been reflected as a compression.

When a compression strikes the closed end of a pipe (the non-yielding part of a pipe), it is reflected as a compression. This is similar to a free-end reflection in strings and springs.

Rarefactions are also reflected as rarefactions from the closed end of the pipe. The standing wave formed in the tube has its maximum air displacement (an antinode) at the open end. This means there will be a pressure node at the open end of the pipe and a pressure antinode at the closed end.

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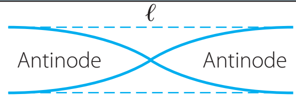
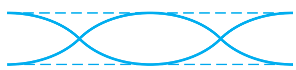
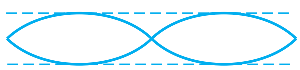
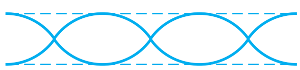
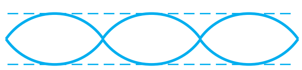
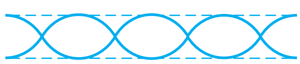
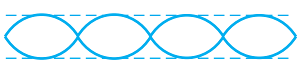
FIGURE 17.3.1 In trombones, the length of the resonator can be changed by sliding one tube through another.

FIGURE 17.3.2 The particle displacement and pressure variations of the resonant frequencies of a tube open at both ends

Vibration mode	Particle displacement	Pressure variation	f and λ
Fundamental mode of vibration 1st harmonic	 ℓ Antinode Antinode	 Node Node	$\lambda_1 = 2\ell$ $f_1 = \frac{v}{2\ell}$
2nd harmonic			$\lambda_2 = \ell$ $f_2 = 2f_1$
3rd harmonic			$\lambda_3 = \frac{2}{3}\ell$ $f_3 = 3f_1$
4th harmonic			$\lambda_4 = \frac{1}{2}\ell$ $f_4 = 4f_1$
5th harmonic			$\lambda_5 = \frac{2}{5}\ell$ $f_5 = 5f_1$

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Stationary waves in open pipes

To indicate the stationary wave pattern in an air column, either the pressure variation or the particle displacement could be used. Figure 17.3.2 represents the particle displacement and pressure variations in an open pipe. In all open pipes, the maximum air displacements (displacement antinode or a pressure node) occur at both ends of the tube, so that its natural frequencies are different from those of a tube closed at one end.

For pipes open at both ends to resonate, the length of the pipe must be related to the resonating wavelength by the relationship:

$$\ell = n\frac{\lambda_n}{2}$$

In open pipes, all harmonics are possible and, as such, the frequency of the resonating tone can be found as:

$$f_n = \frac{v}{\lambda_n} = n\frac{v}{2\ell} = nf_1$$

KEY FORMULA

Relationship between the length of an open pipe and the wavelength of its resonant frequencies

$\ell = n\frac{\lambda_n}{2}$

Where:

ℓ = the length of the string

n = the mode or harmonic number ($n = 1, 2, 3 \ldots$)

λ_n = the wavelength of the nth mode or harmonic

KEY FORMULA

The frequency of resonant tones of an open pipe

$f_n = \frac{v}{\lambda_n} = n\frac{v}{2\ell} = nf_1$

Where:

f_n = the frequency of the nth mode or harmonic

ℓ = the length of the string

n = the mode or harmonic number ($n = 1, 2, 3 \ldots$)

λ_n = the wavelength of the nth mode or harmonic

f_1 = the fundamental frequency

WORKED EXAMPLE 17.3.1

Calculate the wavelength of the fundamental frequency resonating in a flute of length 62 cm, which can be modelled as an open pipe.

ANSWER

State the equation:

$\ell = n\frac{\lambda_n}{2}$

Rearrange for the unknown value:

$\lambda_n = \frac{2\ell}{n}$

Insert known values:

$\lambda_1 = \frac{2 \times 0.62\text{ m}}{1}$

Calculate the answer:

$\lambda_1 = 1.24\text{ m}$

Give the answer to the correct number of significant figures:

$\lambda_1 = 1.2\text{ m}$

WORKED EXAMPLE 17.3.2

Calculate the length of a pipe open at both ends whose fundamental frequency is 320 Hz, when the temperature is such that the speed of sound in the air is 340 m s^{-1}.

ANSWER

State the equation:

$$f_n = n\frac{v}{2\ell}$$

Rearrange for the unknown value:

$$\ell = \frac{nv}{2f_n}$$

Insert known values:

$$\ell = \frac{1 \times 340\ \text{m s}^{-1}}{2 \times 320\ \text{Hz}}$$

Calculate the answer:

$$\ell = 0.531\,25$$

Give the answer to the correct number of significant figures:

$$\ell = 0.53\ \text{m}$$

Stationary waves in closed pipes

Consider an air column that is in a tube closed at one end. When it is resonating, a pressure antinode (displacement node) occurs at the closed end. Figure 17.3.3 represents the particle displacement and pressure variations in a pipe closed at one end.

FIGURE 17.3.3 The particle displacement and a pressure variation representation of the resonant frequencies of a tube closed at one end. All harmonics have maximum particle displacement at the open end and none at the closed end.

Vibration mode	Particle displacement	Pressure variation	f and λ
Fundamental mode of vibration 1st harmonic	 Antinode Node	 Node Antinode	$\lambda_1 = 4\ell$ $f_1 = \frac{v}{4\ell}$
3rd harmonic			$\lambda_2 = \frac{4\ell}{3}$ $f_2 = 3f_1$
5th harmonic			$\lambda_3 = \frac{4\ell}{5}$ $f_3 = 5f_1$
7th harmonic			$\lambda_4 = \frac{4\ell}{7}$ $f_4 = 7f_1$
9th harmonic			$\lambda_5 = \frac{4\ell}{9}$ $f_5 = 9f_1$

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For a closed pipe to resonate, the length of the pipe must be related to the resonance wavelength by the relationship:

$$\ell = (2n-1)\frac{\lambda_n}{4}$$

The fundamental resonance mode when $n = 1$ (1st harmonic)

$$\ell = \frac{\lambda}{4}$$

The resonance mode when $n = 2$ (3rd harmonic):

$$\ell = \frac{3\lambda}{4}$$

The resonance mode when $n = 3$ (5th harmonic)

$$\ell = \frac{5\lambda}{4}$$

Note that only the odd harmonics are present in a closed pipe. This means that musical instruments with one closed end can only produce half the notes that can be produced by instruments containing open ends. The frequencies of the harmonic modes can therefore be calculated as:

$$f_n = \frac{v}{\lambda_n} = (2n-1)\frac{v}{4\ell} = (2n-1)f_1$$

KEY FORMULA

Relationship between the length of a closed pipe and the wavelength of its resonating frequencies.

$$\ell = (2n-1)\frac{\lambda_n}{4}$$

Where:

ℓ = the length of the string

n = the mode number (n = 1, 2, 3 …)

λ_n = The wavelength of the nth mode

KEY FORMULA

The frequency of resonant tones of a closed pipe

$$f_n = \frac{v}{\lambda_n} = (2n-1)\frac{v}{4\ell} = (2n-1)f_1$$

Where:

f_n = the frequency of the nth mode

v = the speed of sound in air

ℓ = the length of the string

n = the mode number (n = 1, 2, 3 …)

λ_n = the wavelength of the nth mode

f_1 = the fundamental frequency

WORKED EXAMPLE 17.3.3

Calculate the wavelength of the second mode of a bamboo pipe closed at one end, if the pipe is 32 cm long.

ANSWER

State the equation:

$$\ell = (2n-1)\frac{\lambda_n}{4}$$

Rearrange for the unknown value:

$$\lambda_n = \frac{4\ell}{2n-1}$$

Insert the known values:

$$\lambda_n = \frac{4 \times 0.32\ \text{m}}{2 \times 2 - 1}$$

Calculate the answer:

$\lambda_n = 0.426\,67$ m

Give the answer to the correct number of significant figures:

$\lambda_n = 0.43$ m

WORKED EXAMPLE 17.3.4

If the speed of sound in a closed organ pipe is 334 m s^{-1}, calculate the length of a pipe that resonates with a fundamental frequency of 57 Hz.

ANSWER

State the equation:

$$f_n = (2n-1)\frac{v}{4\ell}$$

Rearrange for the unknown value:

$$\ell = (2n-1)\frac{v}{4f_n}$$

Insert the known values:

$$\ell = (2\times1-1)\frac{334\ \text{m s}^{-1}}{4\times57\ \text{Hz}}$$

Calculate the answer:

$\ell = 1.4649$ m

Give the answer to the correct number of significant figures:

$\ell = 1.5$ m

SECTION REVIEW 17.3

REMEMBERING

1 Outline the differences between a closed and open pipe in terms of:

a their physical structure

b the wavelengths of their resonant frequencies.

UNDERSTANDING

2 A tube of length ℓ is open at both ends. A stationary wave is set up in the tube. Only waves with certain frequencies will cause resonance within the tube. Which of the following gives the set of wavelengths that can exist in a tube open at both ends ($n = 1, 2, 3, \ldots$)?

A n

B $\frac{\ell}{n}$

C $\frac{4\ell}{2n-1}$

D $\frac{2\ell}{n}$

3 A tube of length ℓ is closed at one end. A stationary wave is set up in the tube. Only waves with certain frequencies will cause resonance within the tube. Which of the following gives the set of wavelengths that can exist in a tube open at both ends ($n = 1, 2, 3, \ldots$)?

A n

B $\frac{\ell}{n}$

C $\frac{4\ell}{2n-1}$

D $\frac{2\ell}{n}$

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APPLYING

4 Water is poured into a long metal tube closed at one end until the shortest resonant length is found for a tuning fork of frequency 256 Hz. If the length of the air column in the tube is 31.0 cm, what is the velocity of sound in the air?

5 The average human ear is most sensitive to sounds of a frequency of about 5000 Hz. The outer ear canal can be modelled as a tube closed at one end (Figure 17.3.4). Assuming that this frequency corresponds to the fundamental frequency, what is the length of the outer ear canal of a human?

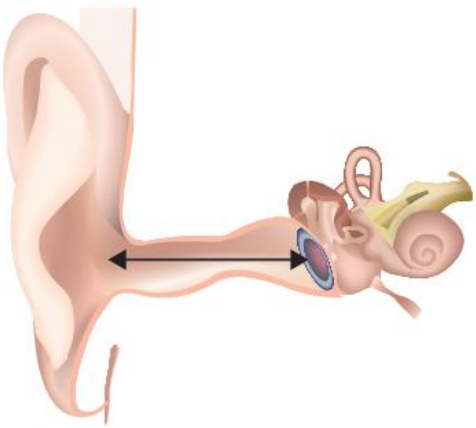

FIGURE 17.3.4

CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1. Define the following terms.
   a. Natural frequency
   b. Forced vibration
   c. Resonance
   d. Driving frequency
   e. Resonant frequency
   f. Harmonic
   g. Open pipe
   h. Closed pipe

CATEGORY QUESTIONS

2. Explain what happens if the driving frequency provided by a vibrating object perfectly matches the resonant frequency of another object.
3. Give an example of an object freely vibrating at its resonant frequency.
4. Explain why an object vibrating at its resonant frequency emits a tone that is sustained for a longer period than if it was vibrating at a different frequency.
5. Explain the process by which a vibrating object can propagate a wave through air and the ear to produce the sensation of sound.
6. Compare the pattern of resonant frequencies that can exist in an open air column with that in a closed air column.

ELABORATION QUESTIONS

7. Suggest reasons for the collapse of the Tacoma Narrows Bridge shortly after it was built.
8. Explain why a vibrating string can be touched in specific positions along its length without bringing the vibration to a halt.
9. The frequency of the maximum sensitivity of hearing for a domestic cat is different from that of humans. The frequency depends on the length of the ear canal. Will the frequency of maximum sensitivity for the cat be higher or lower than that for humans? Explain your answer.

EVIDENCE QUESTIONS

10. What safeguards could have been put in place to prevent the Tacoma Narrows Bridge disaster?
11. Examine a picture of the ear canal of a cat and compare it with that of a human. Is it possible that this has an effect on the range of its hearing? Conduct some research to suggest a reason for the different anatomy.

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END-OF-CHAPTER EXAM

End-of-chapter test

1 The natural frequency of an object is the frequency with which it will vibrate if:

A it is displaced from its equilibrium position repeatedly.

B it is displaced from its equilibrium position and left to vibrate.

C it is placed in the vicinity of another object.

D its elastic properties are altered while vibrating.

2 Which of the following instruments is an example of a closed pipe?

A A clarinet

B A flute

C An organ

D A guitar

3 Which of the following wavelengths corresponds to the second harmonic of a stringed instrument?

A $\lambda = 2\ell$

B $\lambda = \ell$

C $\lambda = \frac{2\ell}{3}$

D $\lambda = \frac{\ell}{2}$

4 Which of the following frequencies corresponds to the fundamental frequency of a closed pipe?

A $f = \frac{v}{4\ell}$

B $f = \frac{3v}{4\ell}$

C $f = \frac{v}{2\ell}$

D $f = \frac{v}{\ell}$

5 What is the term given to the tendency of an object to be induced to vibrate at its natural frequency by another object vibrating at this frequency?

6 What is another name given to the vibration mode of an object?

7 Explain the term 'forced vibration'.

8 Describe what factors determine an object's natural frequency.

9 The fundamental frequency of a 3.0 m long string fixed at both ends is 15 Hz.

a What are the frequencies of the next three harmonics?

b What is the speed of the waves in the string?

c What is the wavelength of the first harmonic?

10 Calculate the length of a pipe that is open at both ends if its fundamental frequency is 280 Hz when the speed of sound is 343 m s^{-1}.

11 The speed of sound in a 2.0 m closed pipe is 340 m s^{-1}.

a Calculate the wavelength of the first three vibrational modes of the pipe.

b Calculate the frequency of the first three vibrational modes of the pipe.

12 Explain the process of producing a note in a clarinet.

13 Draw a diagram of a didgeridoo resonating at its second vibrational mode. On the diagram, show the:

a pressure variation.

b displacement variation.

14 If the average frequency range of human hearing is 20–20 000 Hz, how many of the vibrational modes of a 2.2 m open-ended pipe can be heard if the speed of sound is 340 m s^{-1}?

15 If a 1.8 m open-ended air column resonates at two successive vibrational frequencies of 350 Hz and 450 Hz, calculate the fundamental frequency of the column.

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18 LIGHT

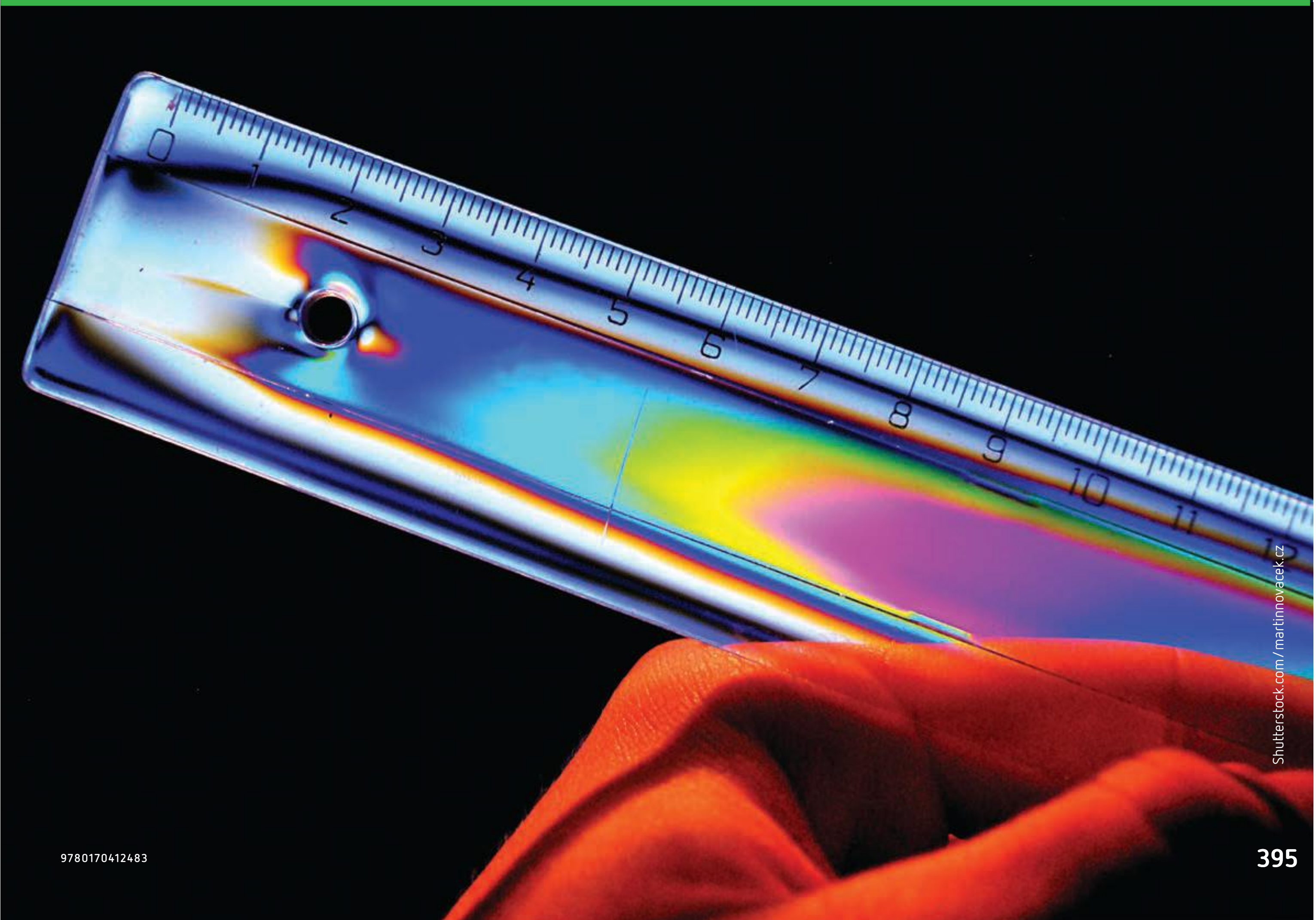
Introduction

'What is light?' This question is somewhat difficult to answer. Light reflects from surfaces, goes through transparent materials and produces electricity in solar cells. If we illuminate a green surface with orange light it appears black. It is the interaction between light and matter that must be explained. The better question, therefore, is: 'What does light act like when it interacts with matter?'

In this chapter we will investigate different models of light and use the wave and ray models to describe the phenomena of light intensity, polarisation, reflection, diffraction and refraction.

Stimulus questions

- What is light?
- What does light act like when it interacts with matter?
- When does light behave like a wave?
- What sort of a wave is light?



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18.1 Models of light

wave–particle duality
the need to model light as both a wave and a particle

ray model
a model that describes light as travelling in rays that change direction during interactions with matter

wave model
a model of that describes light as travelling as waves

photon
a particle of light

In some experiments, light seems to travel as a wave but interact with matter as a particle. These experiments cannot be explained without the use of both the wave and particle models together. Scientists call this need for these two apparently quite different models the **wave–particle duality**. In fact, there are three current models used to explain the propagation of light and the interactions between light and matter.

The ray model

In the **ray model**, light is described as travelling in straight lines (rays) from any source. The rays change direction whenever light interacts with a material. The ray model is useful for analysing the interaction of light with large objects or surfaces such as lenses and mirrors. We can model reflection and refraction using the ray model.

The wave model

In the **wave model**, light is treated as a wave that propagates through a vacuum or a medium with a speed that depends on the electric and magnetic properties of the medium. The wave model is useful for analysing the interaction of light with objects that are similar in size to the wavelength of the light, such as small apertures and obstacles, and the edges of objects. We can model interference and diffraction using the wave model.

SYLLABUS LINK

The photon model and wave–particle duality will be investigated further in Chapter 12 of *Nelson QScience Physics Units 3 & 4*.

The photon (particle) model

Some interactions of light with matter cannot be explained by treating light solely as a wave. To understand these interactions, we model light as consisting of particles called **photons**, each with a characteristic energy. When light interacts with matter, an entire photon, but not part of a photon, may be absorbed (or emitted). This is the quantum particle model of light, as the photons are discrete quanta of light energy.

In this chapter, we shall be using the ray and wave models.

SECTION REVIEW 18.1

REMEMBERING

1 Name the three models of light.
2 What is a photon?

UNDERSTANDING

3 Compare the key features of the three models of light.
4 Why is the question 'What is light?' misleading? How should the question be restated? Why?

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18.2 The wave model of light

Modelling light as a wave is very effective in describing many observed phenomena. However, there is one major difficulty with this model that took many years to resolve: all mechanical waves need some medium to transfer energy, so what exactly do light waves travel through?

The modern understanding of the expanses of space is that it consists of an effective vacuum and, as such, light from objects such as the Sun do not travel through a medium and therefore cannot be considered as mechanical waves.

electromagnetic radiation energy that travels as waves and moves at the speed of light

electromagnetic wave model light acts like a transverse wave that has electric and magnetic components

luminous aether a non-existent substance that was proposed to exist in early wave models of light as the medium through which light could travel

Electromagnetic waves

In the second half of the 19th century, James Clark Maxwell used the new discovery that there was a relationship between electricity and magnetism to construct a mathematical model that predicted the existence of electromagnetic radiation that travelled as waves. His theories suggested that an oscillating electric charge in one direction (E in Figure 18.2.1) causes a magnetic effect at right angles (B in Figure 18.2.1), which would result in an electromagnetic wave travelling off at right angles to both.

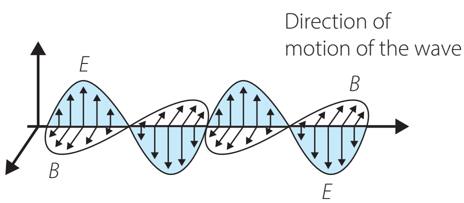

FIGURE 18.2.1 In an electromagnetic wave, the electric (E) and magnetic (B) effects oscillate at right angles to each other, while the wave travels in the third dimension at right angles to both effects.

Maxwell's model explained all the light phenomena that had been observed up until that time and, importantly, explained that these waves could propagate through empty space.

The electromagnetic wave model of light states that, in its interactions with matter, light acts like a three-dimensional transverse wave.

SYLLABUS LINK

Electromagnetic waves is discussed in greater detail in Chapter 10 of *Nelson QScience Physics Units 3 & 4*.

The luminous aether

Considering the success of the mechanical wave theory, it was natural for physicists to assume that if light was a wave it must also travel through some medium. They postulated the existence of a transparent substance that permeated all of space which they called the luminous aether.

In this theory, the aether would be stationary while the Earth travelled through it and therefore light would have to travel at different speeds in different directions. Scientists designed many experiments to observe this prediction. The most famous of these was the Michelson–Morley experiment.

INQUIRING FURTHER

Maxwell's electromagnetic wave theory consists of oscillations in electric and magnetic fields. Investigate field theory and its implications.

SCIENCE AS A HUMAN ENDEAVOUR

In 1880, A.A. Michelson and E.W. Morley used a device called a Michelson interferometer to compare the speed of light in the direction of Earth's orbit and in the direction away from Earth's orbit. They expected to observe different speeds relative to the aether, in the same way that a boat travels faster relative to the bank of a river when it is travelling with the flow of water than when it is travelling against the flow. The fact that they observed no difference at all confused physicists for years until, in 1905, Albert Einstein's theory of relativity reconciled these observations by stating that the speed of light was a fixed constant of the universe regardless of the direction in which it is being observed.

interferometer an instrument that uses wave interference to make precise measurements of the distance travelled by waves in terms of their wavelength

SYLLABUS LINK

Einstein's theory of relativity and its strange predictions is investigated in Chapter 11 of *Nelson QScience Physics Units 3 & 4*.

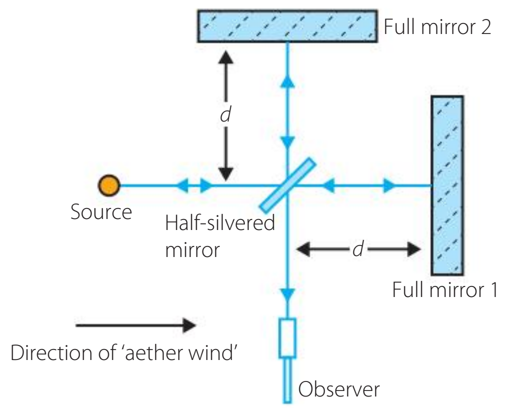

FIGURE 18.2.2 The Michelson–Morley experiment showed that the time taken for light to travel in different directions through the hypothetical luminous aether was the same.

The ray model of light waves

In the ray model of light, light waves are modelled as travelling in straight lines from their source. This can be shown for the waves emanating from a light globe.

These rays represent the direction travelled by the light waves. The waves emanating from a light source can be considered to act like the water waves produced when a stone is dropped into a pond. Each direction is represented by a straight-line ray emanating from the source and acting at right angles to the wavefronts, as in Figure 18.2.4.

If the source of light is being observed from far away, the wavefronts will appear similar to plane waves and the rays will become more parallel. In fact, if the source of light is infinitely far away (and the Sun and stars can be considered as approaching this) these rays would become precisely parallel (see Figure 18.2.5).

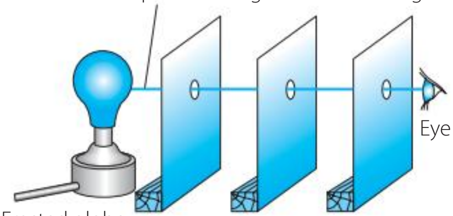

FIGURE 18.2.3 Light travels along a straight line from its source.

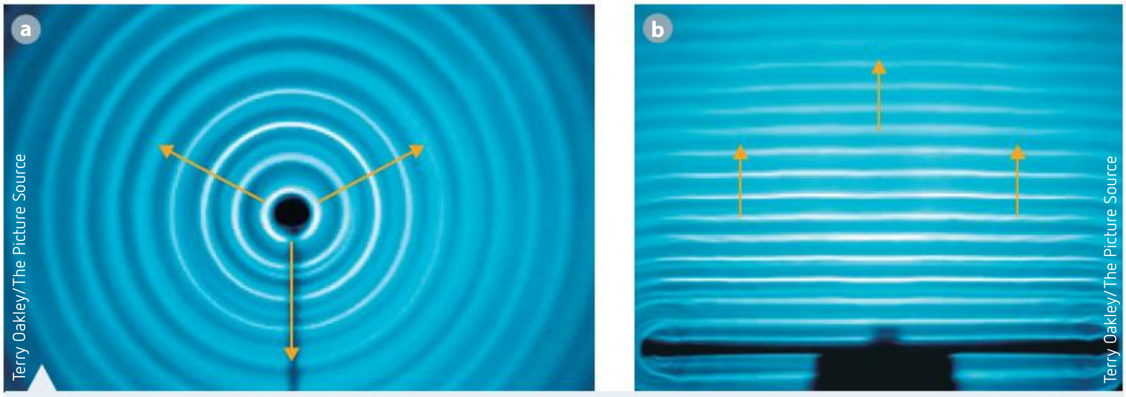

FIGURE 18.2.4 Light rays used in the ray model are always drawn at right angles to the wavefront. (**a**) Circular waves from a point source showing radial rays at right angles to the wavefront; (**b**) straight waves showing rays at right angles to the wavefront

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Sources of light

Luminous light sources (light bulbs, the Sun, lasers) produce light directly by internal processes. **Non-luminous** sources (the Moon, a photographer's silver umbrella) reflect light.

luminous
a source that produces light

non-luminous
a source that reflects light

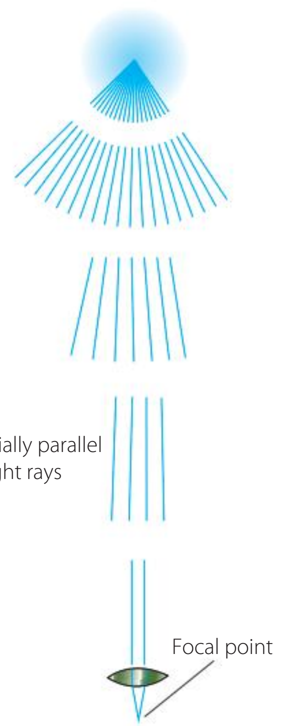

FIGURE 18.2.5 Light rays emanating from a distant source become effectively parallel when viewed from a distance.

Contrasting the speed of light and the speed of mechanical waves

Between 1848 and 1862, Hippolyte Fizeau (1819–96) and Léon Foucault (1819–68) used precision clocks and clockwork motors to make the first terrestrial measurements of the speed of light in air and water. They showed that light travels more slowly in water than in air.

The medium affects the speed of light. Foucault's best result for the speed of light, found in 1862, was 2.998×10^8 m s^{-1}.

The current accepted value for the speed of light in a vacuum and in air is $2.997\,924\,58 \times 10^8$ m s^{-1} (3.0×10^8 m s^{-1}). This is an important constant that is often used, so it is given a unique symbol, *c*. Compare this velocity to that of sound, which travels at about 343 m s^{-1} in air. Light is almost 875 000 times faster than sound!

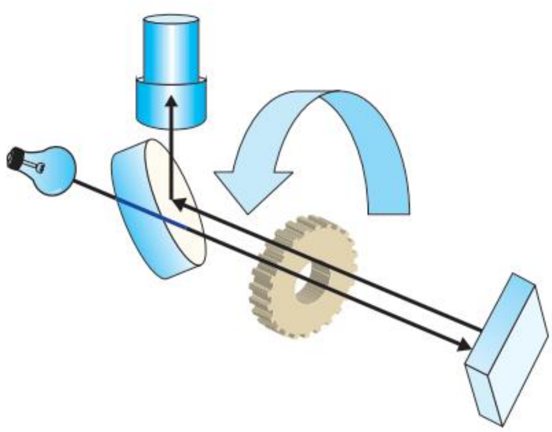

FIGURE 18.2.6 Fizeau's method for measuring the speed of light. A ray of light passes between adjacent teeth of a toothed wheel and is reflected. When the wheel is turned fast enough, the reflected light is blocked by the next tooth.

WORKED EXAMPLE 18.2.1

A race official will traditionally fire a pistol to signal the beginning of a 100 m sprint. Calculate the delay that a spectator standing at the finish line will observe between seeing the flash of smoke from the gun to hearing its sound.

ANSWER

State the correct equation:

$$t = \frac{s}{v}$$

Substitute values for light:

$$t = \frac{s}{v} = \frac{100\text{ m}}{3.0 \times 10^8\text{ m s}^{-1}} = 3.33 \times 10^{-7}\text{ s}$$

Substitute values for sound:

$$t = \frac{s}{v} = \frac{100\text{ m}}{343\text{ m s}^{-1}} = 0.292\text{ s}$$

Find the difference:

$$\Delta t = t_{sound} - t_{light} = 0.292\text{ s} - 3.33 \times 10^{-7}\text{ s} = 0.292\text{ s}$$

The spectator will hear the gun fire 0.292 s after she sees the smoke of the gun.

KEY FORMULA

The speed of light

$c = f\lambda$

Where:

c = the speed of light = 3.0×10^8 m s^{-1}

f = the frequency of the light wave

λ = the wavelength of light

Like all waves, the velocity of light can be calculated from the frequency and wavelength with the formula $v = f\lambda$. But since the speed of light is constant in a given medium, the velocity (v) in this equation can be replaced with a constant (c) representing the speed of light in that medium ($c_{air} = 3.0 \times 10^8$ m s^{-1}).

WORKED EXAMPLE 18.2.2

If a light wave has a wavelength of 450 nm in air, calculate its frequency.

ANSWER

Apply the equation:

$$c = f\lambda$$

Rearrange for the unknown:

$$f = \frac{c}{\lambda}$$

Insert known values (1 nm = 1×10^{-9} m):

$$f = \frac{3 \times 10^8\text{ m s}^{-1}}{450 \times 10^{-9}\text{ m}}$$

Calculate the answer:

$$f = 6.6667 \times 10^{14}\text{ Hz}$$

Give the answer to the correct number of significant figures:

$$f = 6.7 \times 10^{14}\text{ Hz}$$

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Light intensity

Light from a point source spreads uniformly into the surrounding space in much the same way as the energy of mechanical waves. The light intensity is calculated as the energy per unit time (power) that is transported through an area perpendicular to the direction of travel and has units of watts per square metre ($W\,m^{-2}$).

A light wave will travel out in all directions from its source in a three-dimensional sphere. As the wave moves outwards, the energy that was emitted from the source becomes spread over a larger spherical surface (Figure 18.2.7). As a result, the intensity of the wave decreases as the wave gets further from the source.

The intensity at any point can be calculated as the power over the area ($4\pi r^2$):

$$I = \frac{P}{4\pi r^2}$$

If we assume the power at the source is constant, then we can see that the intensity is inversely proportional to the square of the distance from the source:

$$I \propto \frac{1}{r^2}$$

In Figure 18.2.7, if the source (S) emits a wave of power P, then at a distance r from the source the wave has an intensity I_1 of:

$$I = \frac{P}{r^2}$$

which can be rearranged:

$$P = I_1 r^2$$

Similarly, at a distance $2r$ from the source:

$$I_2 = \frac{P}{(2r)^2} = \frac{P}{4r^2}$$

or:

$$P = 4I_2 r^2$$

Since the power of the source, P, is constant:

$$4I_2 r^2 = I_1 r^2$$

or:

$$I_2 = \frac{1}{4} I_1$$

This shows that if the distance doubles ($2r/r = 2$), then the intensity is reduced to a quarter.

KEY FORMULA

Intensity of a wave

$$I = \frac{\frac{E}{t}}{A} = \frac{P}{A}$$

Where:

I = intensity ($W\,m^{-2}$)

E = energy (J)

t = time (s)

A = area (m^{-2})

P = power (W)

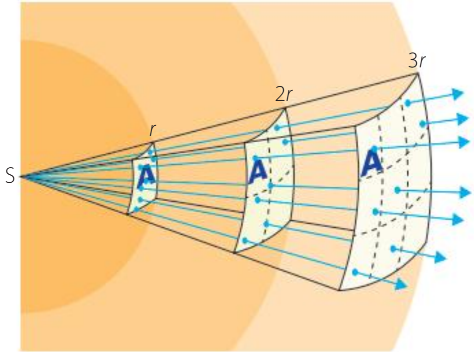

FIGURE 18.2.7 Light from a point source spreads uniformly into the surrounding space.

KEY FORMULA

Light wave intensity

$$I \propto \frac{1}{r^2}$$

Where:

I = intensity ($W\,m^{-2}$)

r = distance from the source (m)

WORKED EXAMPLE 18.2.3

If the wave in Figure 18.2.7 has an intensity of 900 $W\,m^{-2}$ at a distance r from the source, calculate its intensity at a distance $3r$ from the source.

ANSWER

Apply the equation at a distance *r* from the source:

$$I_1 = \frac{P}{r^2}$$

Make *P* the subject:

$$P = I_1 r^2 \qquad (1)$$

Apply the equation at a distance 3*r* from the source:

$$I_3 = \frac{P}{(3r)^2}$$

Expand the bracket and rearrange:

$$I_3 = \frac{P}{9r^2}$$

$$I_3 = \frac{1}{9} \times \frac{P}{r^2} \qquad (2)$$

Substitute equation (1) into equation (2):

$$I_3 = \frac{1}{9} I_1$$

Insert known values:

$$I_3 = \frac{1}{9} \times 900\ \text{W m}^{-2}$$

Calculate the answer:

$$I_3 = 100\ \text{W m}^{-2}$$

Use of the wave model of light to describe phenomena

The wave model of light, coupled with the ray model, is very effective in describing many common observations. This chapter will use these models to investigate polarisation, reflection, total internal reflection, refraction, dispersion, diffraction and interference.

SECTION REVIEW 18.2

REMEMBERING

1 Define the key features of an electromagnetic wave.

2 What is the difference between luminous and non-luminous sources of light?

UNDERSTANDING

3 Explain the great benefit of the electromagnetic theory of light.

4 Explain why light rays emanating from distant objects can be considered parallel.

5 Explain how the wave model of light can explain the intensity law for point sources of light.

APPLYING

6 If the frequency of a light wave is 5.0×10^{14} Hz, calculate its wavelength.

7 If the intensity of light from a constant power light source is 200 W m^{-1} at a distance of 1.5 m from the source, calculate the intensity of light 3.0 m further out.

ANALYSING

8 Discuss how you could use Fizeau's experiment to measure the distance to objects.

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18.3 Polarisation and the transverse wave model

Polaroid material is made from many small, naturally polarising and transparent crystals on a polyvinyl plastic base. When two sheets are arranged so that their polarising planes are parallel, light is transmitted. However, when one sheet is rotated through 90°, no light is transmitted.

Polarisation can be observed in natural and human-constructed environments. It shows that electromagnetic waves are transverse waves. A mechanical analogy or model can be used to explain polarisation. In Figure 18.3.1(a), both slits A and B are arranged vertically. If slit B is placed horizontally, the vertically polarised waves from slit A (**polariser**) cannot pass through slit B (**analyser**), as seen in Figure 18.3.2(b).

Longitudinal waves cannot be polarised. They travel in the same plane, so the oscillations can always go through both slits A and B.

polarisation
orientation in one direction of the electrical part of electromagnetic waves

polariser
material that selects the direction of polarisation

analyser
material that allows or stops polarised electromagnetic radiation

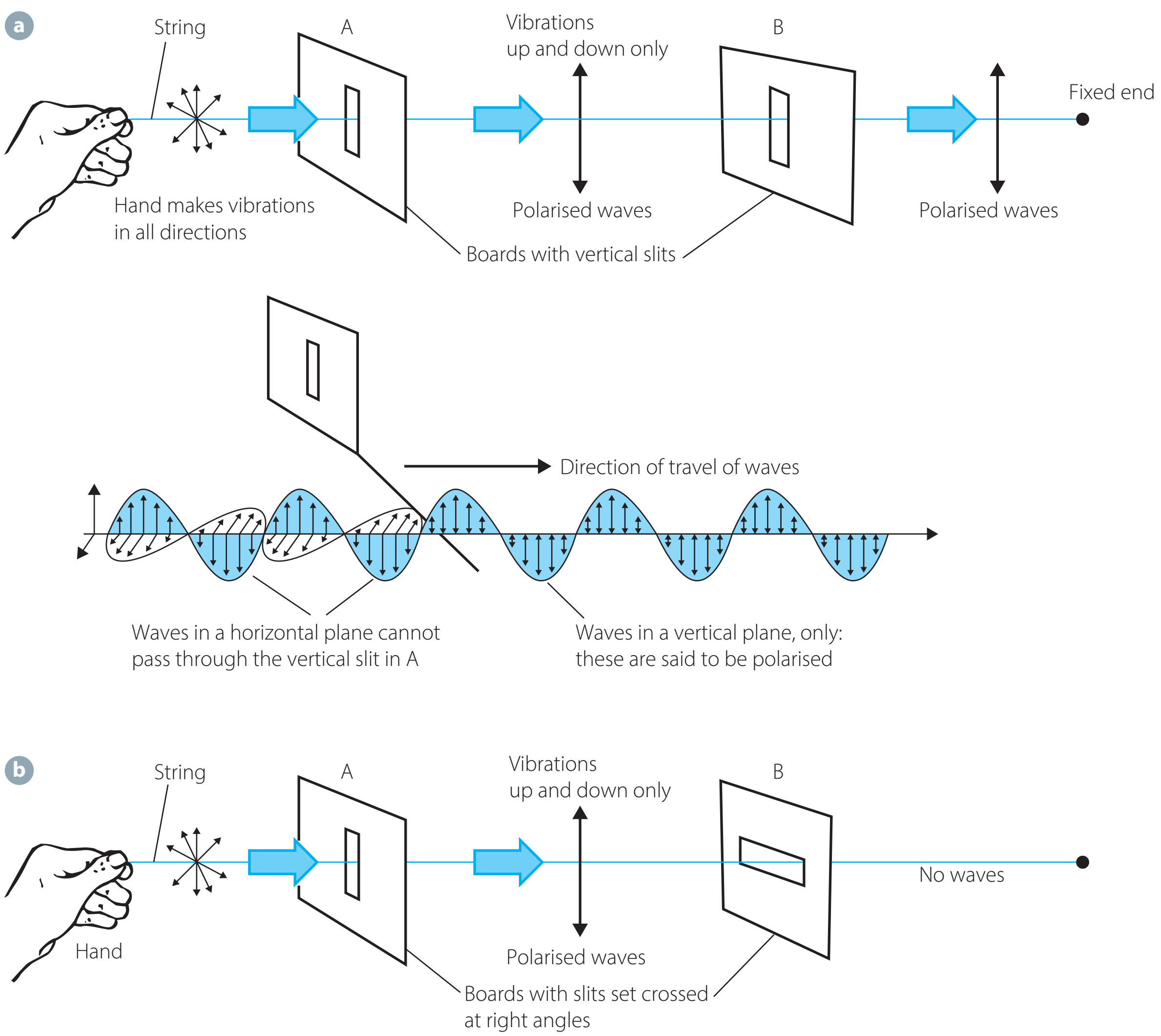

FIGURE 18.3.1 A mechanical model for explaining polarisation. (**a**) Vertically orientated transverse waves pass through slits A and B. (**b**) Vertically polarised waves pass through slit A but cannot pass through slit B, which is perpendicular to A.

SECTION REVIEW 18.3

REMEMBERING

1 Define 'polarisation'.

2 Describe why longitudinal waves cannot be polarised.

UNDERSTANDING

3 Explain the use of the polariser and the analyser in the mechanical model of polarisation.

4 Explain how sunglasses use polarised lenses to reduce the intensity of light from the Sun.

APPLYING

5 Light from an electric globe passes through a polariser. An analyser is placed over the polariser, making the globe look dark. With every quarter turn, the transmitted light goes from a dark minimum to a bright maximum. Use the electromagnetic wave model of light to explain this phenomenon.

18.4 Reflection of light

plane mirror a mirror with a plane (flat) reflecting surface

regular or specular reflection predictable reflection from a very smooth surface; rays in a beam all reflect in the same direction

diffuse reflection (scattering) reflection from a rough surface; rays in a beam reflect in different directions

opaque not transparent; not able to be seen through

When a beam of light is incident on a smooth, polished surface such as a **plane mirror** or a very still water surface, the rays of light forming the beam are reflected in a predictable way. This is **regular** or **specular reflection**.

Most surfaces reflect incident light in all directions. This is known as **diffuse reflection** or **scattering**. For example, a sheet of paper or a painted wall appears smooth, but a microscopic examination of the surface will show it to be rough. Parallel rays incident on a rough surface are scattered in all directions. This is a particularly important property – **opaque** objects are visible from many different angles.

FIGURE 18.4.1 An almost perfect reflection in a still pool of water is an example of specular reflection.

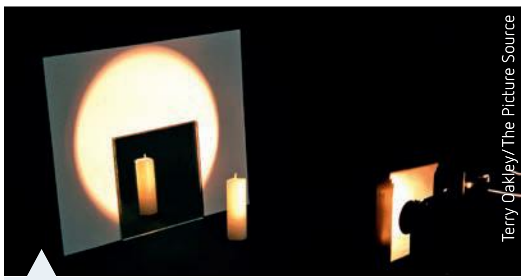

FIGURE 18.4.2 Diffuse and regular reflection from a mirror in front of a white piece of paper. The mirror is mainly dark because light is not reflected to the camera, while the paper reflects light in all directions, including towards the camera. The candle and its image are recorded by diffuse reflection to the camera.

Law of reflection

normal a line drawn perpendicular to a surface

coplanar in the same plane

angle of incidence the angle made between an incident wave and a normal drawn to the surface at the point of incidence

angle of reflection the angle made between a reflected wave and a normal drawn to the surface at the point of incidence

Reflection from surfaces always follows the law of reflection. This is true for specular and diffuse reflection; however, it is easier to observe specular reflection. The law of reflection has two parts.

1 The incident ray, the **normal** perpendicular to the surface, and the reflected ray all lie in the same flat surface (they are **coplanar**).

2 The angle between the incident ray and the normal (the **angle of incidence**) is equal to the angle between the normal and the reflected ray (the **angle of reflection**): $\angle i = \angle r$.

This applies at any point on a surface (Figure 18.4.3). Figure 18.4.3(a) shows the simple case of a flat surface, and hence is specular reflection. Figure 18.4.3(b) shows the case of a rough surface, and hence shows diffuse reflection.

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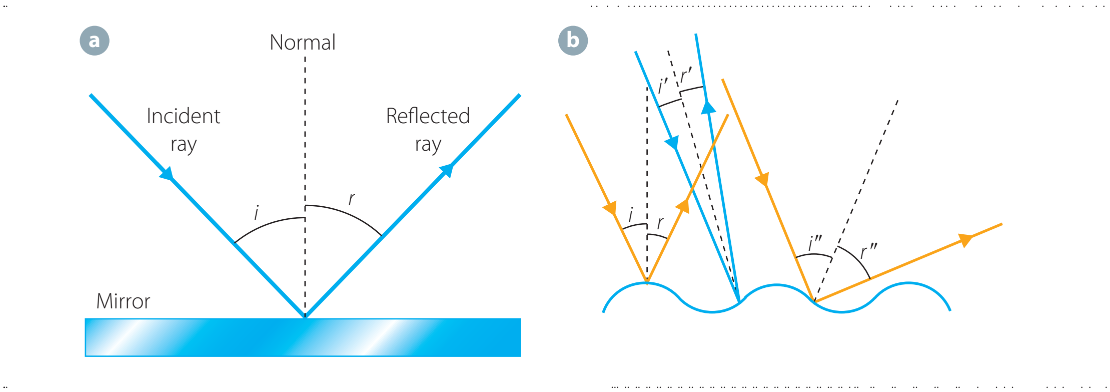

FIGURE 18.4.3 (**a**) Specular reflection; (**b**) diffuse reflection

Solving problems: reflection of light using ray diagrams

Problems involving the reflection and refraction of light waves off mirrors and through lenses can often be diagrammatically solved with the use of the **ray diagram** convention.

In this convention, light rays are drawn both for the incident and for the reflected and refracted rays.

The angles of the rays are measured from the normal to the surface rather than the surface itself. The normal is drawn perpendicular to the surface, and in the plane of the two rays.

Reflection using the ray model

When a person stands in front of a plane mirror, they see a reflection of themselves. This reflection appears to be in front of them, beyond the mirror, but it isn't; it is an **image** of the person.

Light radiates from a **point source** in all directions. When the rays strike a plane mirror, they reflect ($\angle i = \angle r$). They appear to come from an image point, a **virtual image**, behind the mirror. The rays that enter our eyes must affect our retinas. Reflected rays form a **real image** in our eyes. Psychologically, we perceive a virtual image of the object to be where it is not physically present.

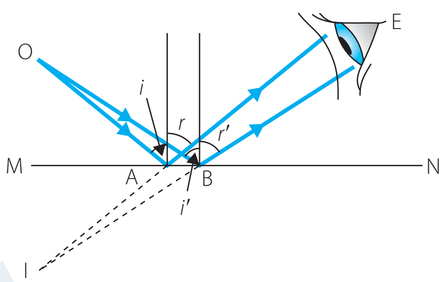

FIGURE 18.4.4 Reflected rays are perceived to be coming from behind the mirror. The image is virtual because the rays do not pass through the image. A real image is formed on the retina of the eye.

Figure 18.4.4 shows how the image is formed and seen by an observer. Rays of light from the object, O, travel to the mirror and reflect such that the angle of incidence is equal to the angle of reflection. Two rays are shown, which reflect at points A and B. When we look towards points A and B on the mirror, it appears that light is coming from these points. If we extend the rays behind the mirror, they intersect at point I behind the mirror. Point I is the position of the image.

Figure 18.4.5 shows a ray diagram that allows us to find the magnification and position of the image. We draw our object as having some actual size, such as the arrow in Figure 18.4.5. We draw rays coming from the top of the object and reflecting from the mirror. The rays must obey the law of reflection as shown. We again extend the reflected rays behind the mirror to the point at which they intersect. This point corresponds to the top of the image, the arrowhead. Our object has a height equal to the distance between the mirror, M, and point O; the image has a height equal to the distance between the mirror, M, and point I. The ratio of these distances is the **magnification**. For a plane mirror, $M = \frac{h_i}{h_o} = 1$.

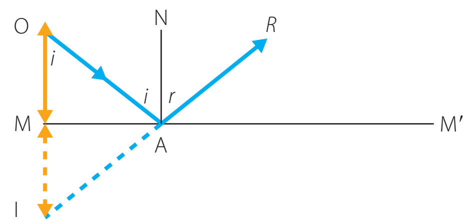

FIGURE 18.4.5 Geometric construction to show the law of reflection

ray diagram
a diagram that traces the path taken by light in order for a person to view an object

image
picture of an object

point source
single localised source from light transmits equally in all directions

virtual image
image of an object where the rays do not pass through the image; the image cannot be projected onto a screen

real image
image of an object where the rays of the image do not pass through the image itself; the image can be projected onto a screen

magnification (*M*)
ratio of image height to object height

SECTION REVIEW 18.4

REMEMBERING

1 Write down both statements for the law of reflection. Draw a diagram to show this law.

2 Use the ray model to illustrate diffuse reflection.

UNDERSTANDING

3 A ray from a point object strikes a plane mirror at an angle of incidence of 30°. Use a carefully measured diagram to show that the object and the image are equidistant on opposite sides of the mirror.

4 How do we see a virtual image in a plane mirror? Use a ray diagram to assist in your explanation.

ANALYSING

5 The eyes of a 170 cm tall woman are 160 cm above the ground. She stands 0.60 m in front of a plane mirror that is mounted vertically and sees her entire image. What is the shortest mirror that can be used for such a purpose? Illustrate your answer with a diagram.

6 Prove that the image is exactly the same distance behind the mirror as the object is in front of the mirror. (MO = MI in Figure 18.4.5, page 405).

18.5 Snell's law and the refraction of light

When a ray of light travels from one transparent medium into another, it changes direction. This phenomenon is called refraction. The amount of refraction is mainly related to differences in the electrical properties of each medium. The electromagnetic wave changes speed depending on how well the electromagnetic wave is permitted to move through the medium.

Refraction is responsible for many strange optical effects, such as the apparent bending of a straight stick that is partly in water and partly in air.

Refractive index

Refraction occurs whenever light passes from one medium into another. We can characterise any medium by its refrangibility. **Refrangibility** is a measure of how much refraction will occur when light moves into a particular material from a vacuum.

The number used to compare refrangibilities is called the **refractive index**. The value of the refractive index of a vacuum is defined as the value 1.00. Other values express the ratio of the refrangibility of a medium to that of a vacuum. Relative to a vacuum, all other values are greater than 1.00 for visible light.

When light moves from one material to a second material with a similar refractive index, there is very little refraction. This is the case when light moves from a vacuum to air, which has a refractive index close to 1.00. When light moves from one medium to a second medium with a very different refractive index, there is strong refraction. For example, diamond has a refractive index of 2.42 for visible light. Hence, light entering a diamond from air is slowed down a lot and bends significantly.

refrangibility a measure of how much refraction will occur when light moves into a particular material from a vacuum

refractive index measure of refrangibility; measure of the relative change of direction of waves or light rays when travelling from one medium to another

Terry Oakley/The Picture Source

FIGURE 18.5.1 A straight stick apparently bends or breaks at the interface between air and water.

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Snell's law of refraction

When a light ray refracts at a boundary between two different transparent media, it makes an angle of incidence (i) with the normal to the boundary in the first medium. The refracted ray makes an **angle of refraction** (r) with the normal in the second medium.

All experiments conducted for refraction at a boundary demonstrate the two laws of refraction.

1 The incident ray, the normal and the refracted ray are coplanar.

2 Snell's law is the quantitative expression of the relationship between the incident and refracted rays:

$$\frac{\sin i}{\sin r} = \text{constant}$$

angle of refraction the angle that the refracted ray makes with the normal

KEY FORMULA

Snell's law of refraction

$$\frac{\sin i}{\sin r} = \text{constant}$$

Where:

i = the angle of incidence

r = the angle of refraction

constant = a constant number (dependent upon the refractive indices of the two media)

WORKED EXAMPLE 18.5.1

If a wavelength of light is incident at 15° upon a substance, it is observed that is has an angle of refraction of 25°. Calculate the angle of refraction that would result if the angle of incidence was increased to 21°.

ANSWER

State the equation:

$$\frac{\sin i}{\sin r} = \text{constant}$$

Since the equation is true for both scenarios:

$$\frac{\sin i_1}{\sin r_1} = \frac{\sin i_2}{\sin r_2}$$

Rearrange for the unknown value:

$$\sin r_2 = \sin i_2 \frac{\sin r_1}{\sin i_1}$$

Insert known values:

$$\sin r_2 = \sin(21°)\frac{\sin(25°)}{\sin(15°)}$$

Calculate:

$$\sin r_2 = 0.5852$$

Rearrange to find the unknown:

$$r_2 = \sin^{-1}(0.5852)$$

Calculate the answer:

$$r_2 = 35.815°$$

Give the answer with the correct number of significant figures:

$$r_2 = 36°$$

Snell's law for waves

Figure 18.5.2 shows the wavefronts of waves moving from deep water into shallow water. The waves are bending towards the normal, from which it can be deduced that they are slowing down. The wavelength is also changing when this happens – it is becoming shorter. Figure 18.5.3 is a schematic diagram showing the wavefronts and interface in Figure 18.5.2.

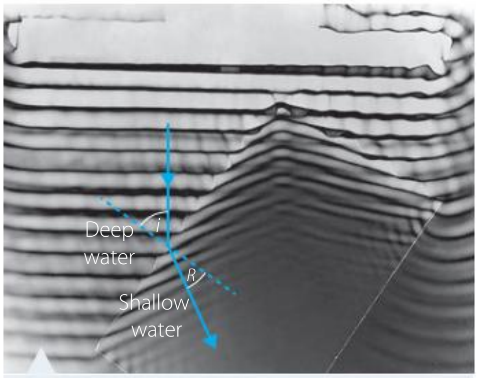
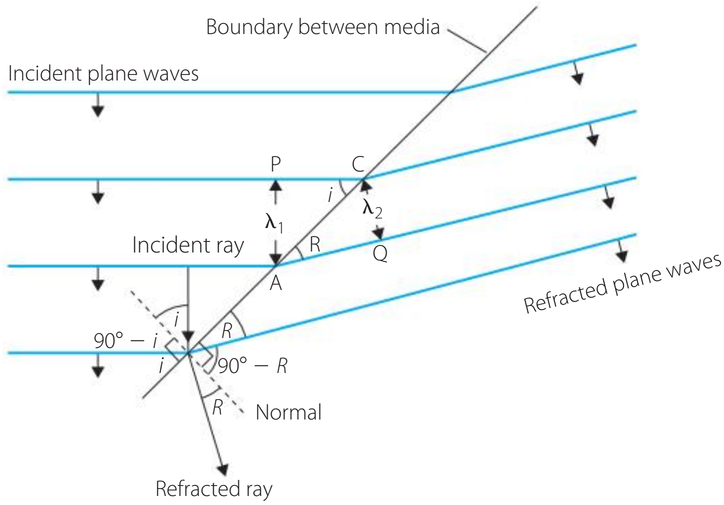


FIGURE 18.5.2 Water waves in deeper water refract towards the normal when they pass into shallower water. Their speed in the shallower water is less than in the deeper water.

FIGURE 18.5.3 Schematic of refraction of waves. Incident rays in medium 1 and refracted rays in medium 2 are drawn at right angles to the wavefronts. Wavelengths λ_1 and λ_2 relate to medium 1 and 2 respectively.



When light crosses the interface between two media it may slow down or speed up, depending on the difference in the optical properties of the media. This difference is encapsulated in the relative difference between the refractive indices. If the light slows down, then the ray that describes its direction of travel bends towards the normal to the interface. If the light speeds up, then it bends away from the normal. Hence, in Figure 18.5.3 in which light is shown bending towards the normal when it moves from medium 1 into medium 2, the light must be slowing down as it crosses the interface.

The geometry of Figure 18.5.3 can be used to show two useful results:

$$\frac{\sin i}{\sin r} = \frac{\lambda_1}{\lambda_2} \quad \text{and} \quad \frac{\sin i}{\sin r} = \frac{v_1}{v_2}$$

In ΔACP:

$$\sin i = \frac{\lambda_1}{AC}$$

and in ΔACQ:

$$\sin r = \frac{\lambda_2}{AC}$$

Thus:

$$\frac{\sin i}{\sin r} = \frac{\lambda_1/AC}{\lambda_2/AC}$$

Finally:

$$\frac{\sin i}{\sin r} = \frac{\lambda_1}{\lambda_2}$$

This result enables us to show the ratio of speeds. The waves enter and leave the boundary at the same rate because the frequency of the waves does not change. From the equation $v = f\lambda$, we can easily show that:

$$\frac{f\lambda_1}{f\lambda_2} = \frac{v_1}{v_2}$$

or:

$$\frac{\lambda_1}{\lambda_2} = \frac{v_1}{v_2}$$

So:

$$\frac{\sin i}{\sin r} = \frac{v_1}{v_2}$$

This expression shows that waves slow down in a medium in which the wavelength decreases and the refraction is towards the normal. The speed decrease is not a cause of the refraction. Neither is the decrease in wavelength a cause of the speed change. The speed decreases because of the interaction of the waves with the medium. For electromagnetic radiation, this means that the different materials have different electrical and magnetic properties. It is the interaction of light with these properties of the materials that causes the change of speed.

Absolute refractive index

absolute refractive index
a measure of the refrangibility of a medium placed in a vacuum and subjected to an incident ray of light

The **absolute refractive index** is a measure of the refrangibility of a medium placed in a vacuum and subjected to an incident ray of light. Each absolute refractive index is experimentally determined. Refractive index is one of the ways by which materials can be identified. Notice that we often shorten 'absolute refractive index' to 'refractive index', when it is clear what we mean (see Table 18.5.1).

TABLE 18.5.1 Refractive indices of some common materials

MATERIAL	Vacuum	Air	Water	Crown glass	Flint glass	Diamond
REFRACTIVE INDEX	1.0000	1.0003	1.33	1.52	1.65	2.42

Air has almost the same refractive qualities as a vacuum. In fact, the two media do not differ until the fourth decimal place. Rounded to two decimal places, the two media are effectively the same, which is why air is usually used as a good approximation to a vacuum in cases where very high levels of accuracy are not required.

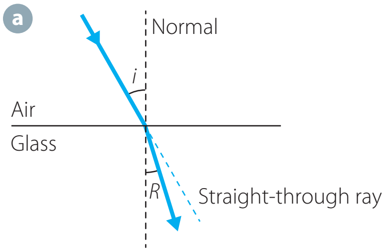
Relative refractive index

relative refractive index
the comparative difference in refrangibility between two media with different absolute refractive indices

The **relative refractive index** is the comparative difference in refrangibility between two media with different absolute refractive indices. From Table 18.5.1, we see that water is 1.33 times, and diamond is 2.42 times, more refractive than air. If a diamond is placed in water, its refrangibility is reduced – it is only $\frac{2.42}{1.33} = 1.82$ times as refractive as it is in air: ($n_{\text{diamond rel water}} = 1.82$). This is still highly refractive compared with various types of glass.

If a piece of sand, $n_{\text{sand}} = 1.46$, is placed in oleic acid of a similar colour, $n_{\text{oleic acid}} = 1.46$, it cannot be distinguished optically from the oleic acid because their refractive indices are the same:

$$n_{\text{sand rel oleic acid}} = \frac{1.46}{1.46} = 1.00$$



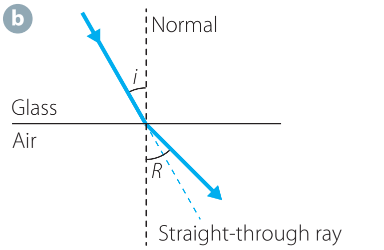


FIGURE 18.5.4 (**a**) Refraction at the air–glass boundary is towards the normal, (**b**) but away from the normal when the rays are reversed (glass–air).

The relative difference in refractive index between two media does not have to be very much for the effect to be noticed. Hot air has a slightly lower refractive index than cold air, of the order of 0.1%, yet this difference is why we can see a shimmering heat haze above a fire or near the road surface on a hot day. We shall see that quite small differences in the refractive indices of different types of glass enables light to travel very efficiently down optical fibres.

Refraction towards and away from the normal

Relative refractive indices can be greater than or less than 1.00. If the relative refractive index is greater than 1.00, then the refracted ray deviates from the straight-through ray towards the normal. Figure 18.5.4(a) shows a ray refracting towards the normal as it travels from air to glass. The relative refractive index is:

$$n_{\text{glass rel air}} = \frac{1.33}{1.00} = 1.33$$

If the relative refractive index is less than 1.00, then the refracted ray deviates away from the normal.

If the rays are reversed and travel from glass to air (Figure 18.5.4(b)), the relative refractive index becomes less than 1.00, and refraction away from the normal occurs:

$$n_{\text{air rel glass}} = \frac{1.00}{1.33} = 0.75$$

Snell's law for waves

In defining refrangibility in terms of relative refractive indices, we have used the general form of Snell's law:

$$\frac{\sin i}{\sin r} = \frac{n_2}{n_1}$$

Combining this with the expression of Snell's law for waves, we can summarise Snell's law as follows:

$$\frac{\sin i}{\sin r} = \frac{\lambda_i}{\lambda_R} = \frac{v_i}{v_R} = \frac{n_R}{n_i} = \text{constant}$$

KEY FORMULA

Snell's law for waves

$$\frac{\sin i}{\sin r} = \frac{\lambda_i}{\lambda_R} = \frac{v_i}{v_R} = \frac{n_R}{n_i} = \text{constant}$$

Where:

i = angle of incidence

r = angle of refraction

λ_i = wavelength of the incident wave

λ_R = wavelength of the refracted wave

v_i = velocity of the incident wave

v_R = velocity of the refracted wave

n_i = refractive index of the medium in which the incident wave is travelling

n_R = refractive index of the medium in which the refracted wave is travelling

constant = relative refractive index of the two media

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WORKED EXAMPLE 18.5.2

Light of wavelength 550 nm travels in water ($n_w = 1.33$) before it strikes the interface with flint glass ($n_g = 1.65$) at an angle of 36° to the normal.

a What is the wavelength of the light in flint glass?

b What is the angle of refraction in the glass?

c Draw a diagram of the scenario.

d If the light has a velocity of 1.81×10^8 m s^{-1} when it is in the flint glass, with what velocity must it have been travelling in water?

ANSWERS

a State the equation:

$$\frac{\lambda_i}{\lambda_R} = \frac{n_R}{n_i}$$

Rearrange for the unknown value:

$$\lambda_R = \frac{\lambda_i \times n_i}{n_R}$$

Insert the known values:

$$\lambda_R = \frac{550 \times 10^{-9} \text{ m} \times 1.33}{1.65}$$

Calculate the answer:

$\lambda_R = 4.433 \times 10^{-7}$ m

Give the answer in the correct format and with the correct number of significant figures:

$\lambda_R = 440$ nm

b State the equation:

$$\frac{\sin i}{\sin r} = \frac{n_R}{n_i}$$

Rearrange for the unknown value:

$$\sin r = \frac{n_i \times \sin i}{n_R}$$

Insert known values:

$$\sin r = \frac{1.33 \times \sin 36°}{1.65}$$

Calculate:

$\sin r = 0.477$

Rearrange:

$r = \sin^{-1}(0.477)$

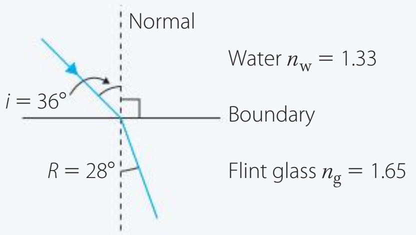
Calculate the answer:

$r = 28.28°$

Give the answer with the correct number of significant figures:

$r = 28°$

c



d State the equation:

$$\frac{v_i}{v_R} = \frac{n_R}{n_i}$$

Rearrange for the unknown value:

$$v_i = \frac{n_R \times v_R}{n_i}$$

Insert the known values:

$$v_i = \frac{1.65 \times 1.81 \times 10^8 \text{ m s}^{-1}}{1.33}$$

Calculate the answer:

$v_i = 2.245\,488\,72 \times 10^8$ m s^{-1}

Give the answer in the correct format and with the correct number of significant figures:

$v_i = 2.25 \times 10^8$ m s^{-1}

Total internal reflection

critical angle
angle of incidence for which the angle of refraction is 90° (total internal reflection occurs); beyond the critical angle, reflection but no refraction occurs

At every boundary between media, reflection always occurs. Mostly, so does refraction. However, for refraction away from the normal, there is an angle of incidence for which no refraction occurs. At angles of incidence greater than this **critical angle** (i_c), the ray is totally reflected back into the medium in which it was travelling when it reached the boundary. At the critical angle of incidence, the refracted angle is 90°.

Thus:

$$\frac{\sin i}{\sin r} = \frac{n_2}{n_1}$$

but, at the critical angle, $i = i_c$ and $r = 90°$.

So:

$$\frac{\sin i_c}{\sin 90°} = \frac{n_2}{n_1}$$

or:

$$\frac{\sin i_c}{1} = \frac{n_2}{n_1}$$

The critical angle can be calculated for any two substances as long as their relative refractive index is also less than one (i.e. $n_2 < n_1$). If the angle of incidence exceeds this critical angle, total internal reflection will occur and no light will be refracted.

KEY FORMULA

The critical angle

$$i_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

Where:

i_c = critical angle

n_2 = refractive index of the second medium

n_1 = refractive index of the first medium

WORKED EXAMPLE 18.5.3

Calculate the critical angle for light that is travelling in flint glass if the light is incident on a boundary with crown glass.

ANSWER

Apply the equation:

$$i_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

Insert known values:

$$i_c = \sin^{-1}\left(\frac{1.33}{1.65}\right)$$

Calculate the answer:

$i_c = 53.713°$

Give the answer to the correct number of significant figures:

$i_c = 53.7°$

Fibre optic cables

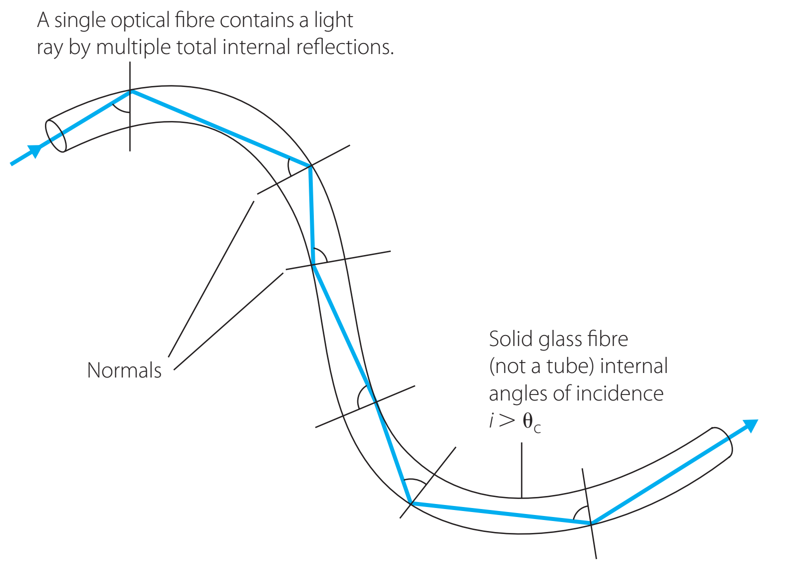


FIGURE 18.5.5 An optical fibre is made from core and cladding glass, and carries light around corners by total internal reflection.

An **optical fibre** is made of a glass **core** that has a refractive index slightly higher than that of the surrounding glass **cladding**.

In this way, light that spreads to the boundary is mostly constrained to travel down the core by total internal reflection. The energy loss per reflection is about 500 times less than for a highly polished mirror surface. Optical fibres are highly flexible so that the light can be readily carried around corners. Every bend causes an increase in energy loss, but this is still much better than for ordinary mirror surfaces.

optical fibre
transparent light guide making use of total internal reflection at a boundary between materials of similar refractive index

core
inner glass of optical fibre

cladding
outer glass of an optical fibre

chromatic dispersion
occurs because different colours refract by different amounts in the same medium; colours spread

Dispersion

Different colours of light refract by different amounts. This effect is called **chromatic dispersion**. Red light refracts least, blue light refracts most: $n_{red} < n_{blue}$. Rainbows are a result of colour dispersion. Colours disperse in every drop and the raindrops produce different colours at slightly different angles.

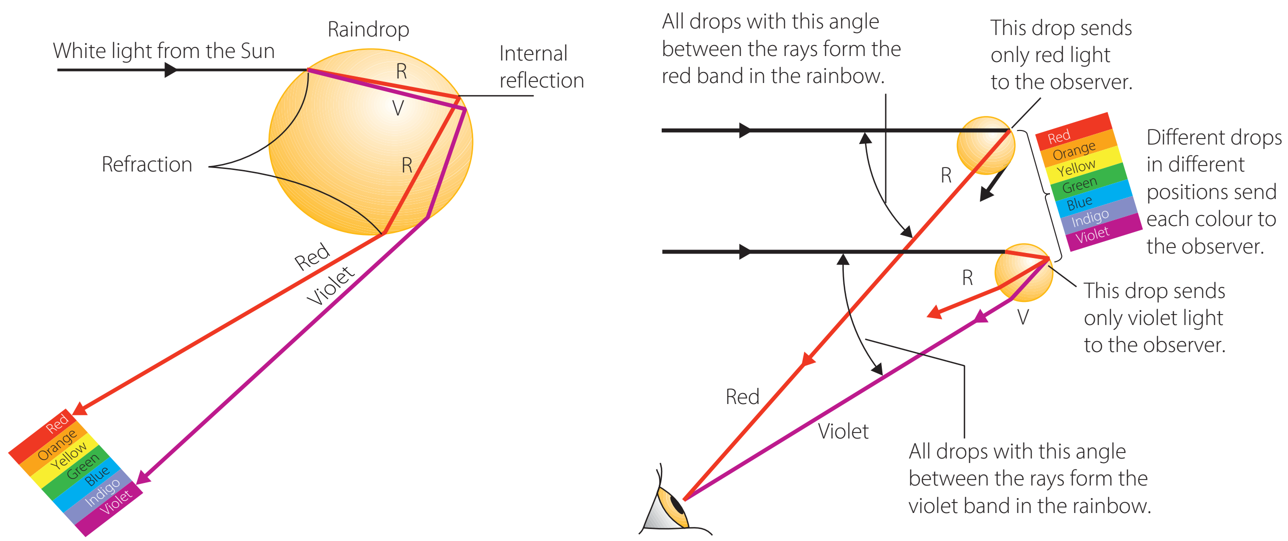


FIGURE 18.5.6 A rainbow is formed by the addition of the dispersed light coming from all the raindrops.

TABLE 18.5.2 Refractive indices for different-coloured light in two types of glass

COLOUR	CROWN GLASS	FLINT GLASS
Red	1.514	1.638
Yellow	1.520	1.650
Blue	1.527	1.664
Violet	1.533	1.675

Solving problems: ray diagrams and refraction through lenses

Ray diagrams can be useful when solving problems involving the refraction of light through a lens. These problems can involve magnification, position, orientation and the nature of the formed image. This is an important skill to many scientists whose experiments rely on the precise manipulation and focusing of light. It is equally important to opticians who use it to restore clear vision to many.

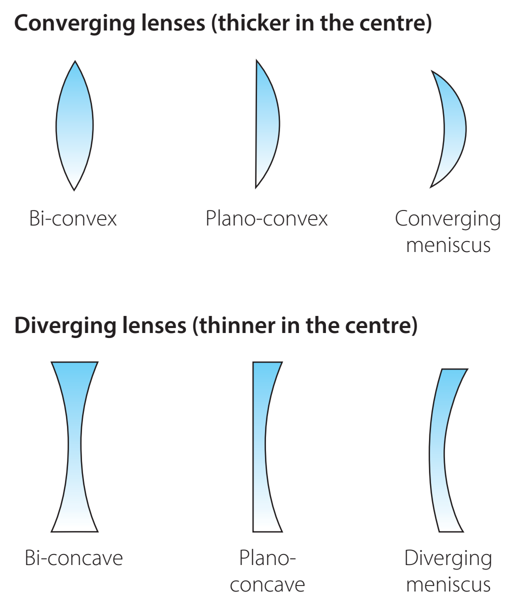
converging (convex) lens
lens thicker in the middle than at the end

diverging (concave) lens
lens that is thicker at the edges than in the middle

Lenses

Lenses are shaped, transparent objects. They may be convex, like the lens in the eye, or concave. A **converging (convex) lens** is thicker at the centre than at the edges. **Diverging (concave) lenses** are thicker at the edges than at the centre. Lenses can produce real or virtual images by refraction.

FIGURE 18.5.7 Types of converging and diverging lenses



Key optical features of lenses

Figure 18.5.8 shows how rays of light are refracted in converging (convex) and diverging (concave) lenses.

FIGURE 18.5.8 Rays that are parallel to the principal axis refract to a real focus (F) in a converging lens, and in line with a virtual focus in a diverging lens.

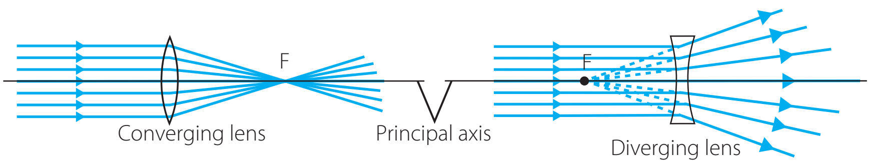


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Figure 18.5.9 shows the geometry of a convex lens system.

The **principal axis**, or axis, is a line that passes through the centre of the lens at right angles to the plane in which the lens stands (the lens axis). The **optical centre** is the point at which these two axes cross. The **focal point**, or focus nearest the object is at the **focal length**, *f*. There is also another focal point placed symmetrically on the opposite side of the lens. The focal point is so named because it is the point to which light that is parallel to the axis of a lens is focused.

principal axis line through both focus and centre and perpendicular to the axis of a curved lens

optical centre centre of curvature of a lens

focal point the point to which light which is parallel to the axis of a lens is focused

focal length distance from lens to focal point

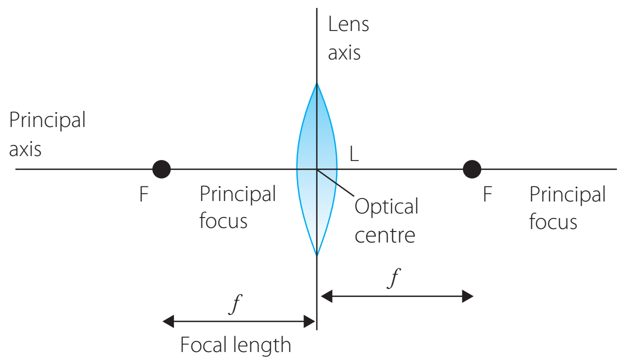


FIGURE 18.5.9 Geometry of the convex lens image-forming system showing lens axis, principal axis, optical centre and two foci

Paraxial assumptions

In order to use ray diagrams to solve problems involving refraction and image formation in lenses, it is necessary to make the following paraxial assumptions.

1. The rays striking the lens are not too far away from the principal axis.
2. The lens is small and thin so that it can be replaced in the diagram with a straight line. (However, we always draw a small lens around the centre to remind us of what we are doing.)
3. When a ray strikes the straight line that represents a lens, it refracts as though the line were the lens or curved mirror.

Convex lens refraction

The convex (converging) lens refracts parallel incoming rays towards the principal axis. The rays converge and cross at the focal point on the opposite side of the lens to the source of the light. The converging lens forms a real image on the opposite side of the lens to the object. A real image is one for which the light is *actually* coming from the point it appears to be coming from. A screen placed at this point will have an image on it, and a photodetector placed at this point will detect light.

Of the millions of rays striking a lens, three are useful to help trace the rays to the image in a convex lens.

- A ray parallel to the axis refracts through the lens and passes through the principal focus on the other side (R_1 in Figure 18.5.10).
- A ray through the focus nearer the object refracts at the lens and travels parallel to the axis (R_2 in Figure 18.5.10).
- A ray directed through the centre of the lens travels to the image unrefracted (R_3 in Figure 18.5.10).

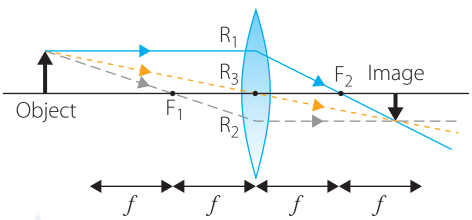


FIGURE 18.5.10 Ray diagram for a converging (convex) lens showing the three useful rays for finding the image

If drawn correctly, these rays will intersect on the opposite side of the lens. This is where the image will be formed. If the initial object's height and distance from the lens is drawn to scale, the height of the image and its distance from the lens can then be calculated by using the same scale.

The image can then be described in terms of its:

- size
- distance from the lens
- magnification (using the formula $M = \frac{\text{height of image}}{\text{height of object}} = \frac{h_i}{h_o}$)
- nature (virtual or real)
- orientation (upright or inverted).

WORKED EXAMPLE 18.5.4

An object 3.0 cm high is placed 16.0 cm in front of a converging lens of focal length 10.0 cm. Use an accurately drawn ray tracing diagram to find:

a the position of the image.

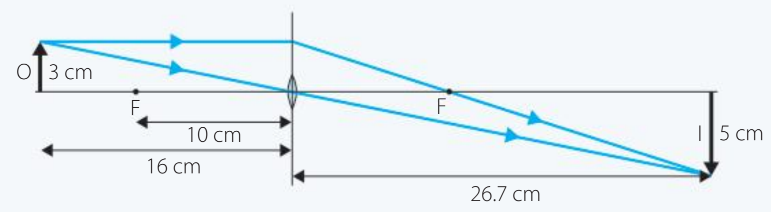
b the nature of the image.

c the size of the image.

d the magnification of the image.

ANSWERS

FIGURE 18.5.11 Ray-tracing diagram showing a real, inverted image formed by a concave lens



a Draw the axes correctly, label the foci and mark in the object correctly. Use a consistent scale.
Draw two useful rays to and from the mirror.
Locate the image correctly. It must be located correctly, both horizontally and vertically.
From the accurately drawn ray diagram, the image is 26.7 cm from the lens on the opposite side from the object.

b From the accurately drawn ray diagram, the image is real but inverted.

c From the accurately drawn diagram, the size is 5 cm.

d Apply the equation:

$M = \frac{h_i}{h_o}$

Insert values taken from the accurately drawn diagram:

$M = \frac{-5\text{ cm}}{3\text{ cm}}$

Calculate the answer with the correct number of significant digits:

$M = 1.7$

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Concave lens refraction

The concave (diverging) lens refracts light so that the parallel rays diverge, and do not cross each other on the far side of the lens from the source. However, if we trace the rays backwards from the right-hand side of the lens we see that they appear to originate from the focal point on the same side of the lens as the object. A diverging lens forms a virtual image, which is an image formed at a position where the light rays do not actually converge. A photodetector placed at this point will not detect light, nor will a screen show an image here. This is similar to the way a plane mirror forms a virtual image. The image still exists, and can be seen and photographed. It is just not due to light coming from the image position; rather the light making the image is being collected by the lens to form a real image in the camera.

Three rays are useful in a concave lens ray diagram:

- A ray parallel to the axis refracts through the lens and diverges at an angle that looks as if it comes from the principal focus on the same side as the object (R_1 in Figure 18.5.12).
- A ray that is directed towards the focus on the other side of the lens passes through and continues parallel to the axis once it reaches the lens (R_2 in Figure 18.5.12).
- A ray directed through the centre of the lens (R_3 in Figure 18.5.12) passes through unaffected.

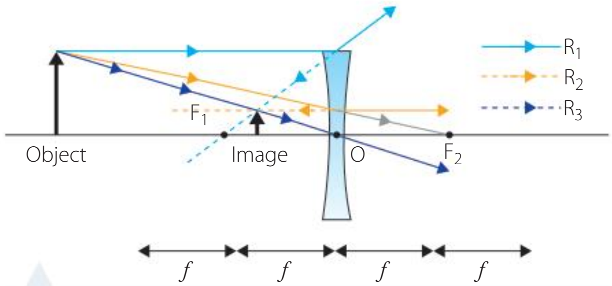


FIGURE 18.5.12 Ray diagram for a diverging (concave) lens showing the three useful rays for finding the image

If drawn correctly, these rays will look like they originate from a point on the same side of the lens as the object and will once again give an indication of the size, distance from the lens, magnification, nature and orientation of the image formed.

MANDATORY PRACTICAL APPLICATION 18.5.1

Snell's law

Refraction can occur when a light ray travels from one medium into another. The effect depends on the angle of incidence and the relative difference in the optical properties of the media.

AIM

To determine the refractive indices of different materials

MATERIALS

- semicircular glass block
- semicircular plastic or glass dish
- ruler
- protractor
- pencil
- black, fine point marker
- graph paper

PROCEDURE

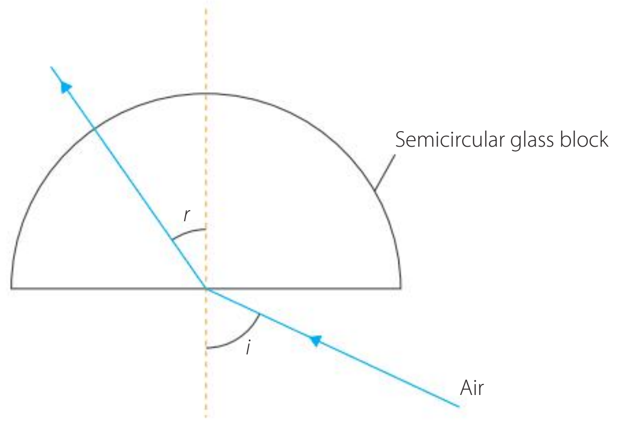
1. Draw a line to divide the graph paper.
2. On the semicircular glass block, draw a vertical line at the centre of the curved edge. (This is your object.)

»

»

3 Place the straight edge of the semicircular glass block along the line on the graph paper.
4 Trace the outline of the block.
5 Mark the point where the vertical black line meets the graph paper.

FIGURE 18.5.13 Arrangement for finding the refractive index of different materials



6 Look towards the straight edge and observe the position of the black line.
7 Use the ruler to draw the sight line towards the object.
8 Repeat this for five different viewing angles.
9 Remove the glass block.
10 For each observation:
   a Draw lines from the object position to the point where the sight line touches the block.
   b Construct the normal at the glass block.

RESULTS

1 Record the following data in a properly constructed data table.
   a Raw data:
      i angle of incidence, i
      ii angle of refraction, r
   b Derived data:
      i $\frac{i}{r}$ ii $\sin i$ iii $\sin r$

ANALYSIS OF RESULTS

1 Plot the following graphs:
   a $\frac{i}{r}$ versus i b $\sin r$ versus $\sin i$

DISCUSSION

1 Is the ratio $\frac{i}{r}$ constant for all values of i?
2 Explain how you can derive the refractive index of glass from the graph of sin R versus sin i.
3 How was the reversibility of light used in this experiment to find the refractive index of glass?
4 Provide an estimate of the uncertainty in the value of the refractive index.
5 Repeat this experimental procedure and analysis with a variety of liquids in the semicircular dish.

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SECTION REVIEW 18.5

REMEMBERING

1 Draw a diagram of light refraction to illustrate the:
   a angle of incidence.
   b angle of refraction.
   c normal.

2 State Snell's law.

3 Define 'absolute refractive index'. Why is it necessary to use a specific wavelength of light in the definition?

UNDERSTANDING

4 An absolute refractive index is really an example of a relative refractive index. Explain.

5 Draw and label an optical fibre to show the core, cladding and total internal reflection at the core–cladding boundary.

6 Explain the key differences between convex and concave lenses.

APPLYING

7 A ray of light of wavelength 981 nm travels in air at a speed of 3.00×10^8 m s^{-1}. It meets a transparent medium of refractive index 1.39 at an angle of 25°.
   a Calculate the frequency of the light in:
      i air.
      ii the transparent medium.
   b Calculate the speed of the light in the transparent medium.
   c What is the angle of refraction as the light passes into the transparent medium?

8 An object 5.0 cm tall is placed 20 cm in front of a convex lens of focal length 10 cm. Use an accurate drawing to determine the distance of the image from the mirror.

ANALYSING

9 Red laser light is incident at the core from air and travels in an optical fibre.
   a What is the critical angle at the core–cladding boundary?
   b What is the maximum angle of refraction at the air–core boundary to ensure all the red light is transmitted down the fibre?
   For red light: $n_{core} = 1.495$, $n_{cladding} = 1.480$

10 An object is placed 20.0 cm in front of a converging lens, and an inverted image three times the size of the object is obtained.
   Show this situation with a geometric scale drawing and determine the focal distance.

18.6 Diffraction

Diffraction occurs when a narrow beam of light passes through a narrow gap, and spreads out into the space beyond. Diffraction is regarded as a wave effect; thus light diffraction through a single gap is explained by analogy with wave phenomena – the wave model – with which we are familiar.

When light is incident on a narrow gap, it forms a distinctive diffraction pattern (Figure 18.6.1) that shows 'structure'. It has a large central bright spot, and less intense bright patches on each side. Between the bright patches are dark patches.

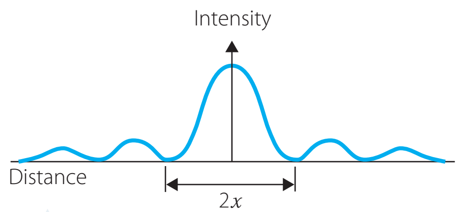

FIGURE 18.6.1 Intensity vs distance from the centre for a single-slit diffraction pattern

In the wave model, the angular spread of the bright central patch, θ, is explained in terms of the wavelength of the light, λ, and the slit width (w):

$$\theta \propto \frac{\lambda}{w}$$

Diffraction effects become noticeable when wavelength and slit width are comparable. This means that when $\frac{\lambda}{w} > 1 \Rightarrow \lambda > w$, the light simply spreads into most of the area, and the central maximum is quite wide (large θ).

Diffraction effects are more pronounced when the ratio is large:

$$\frac{\lambda}{w} \gg 1$$

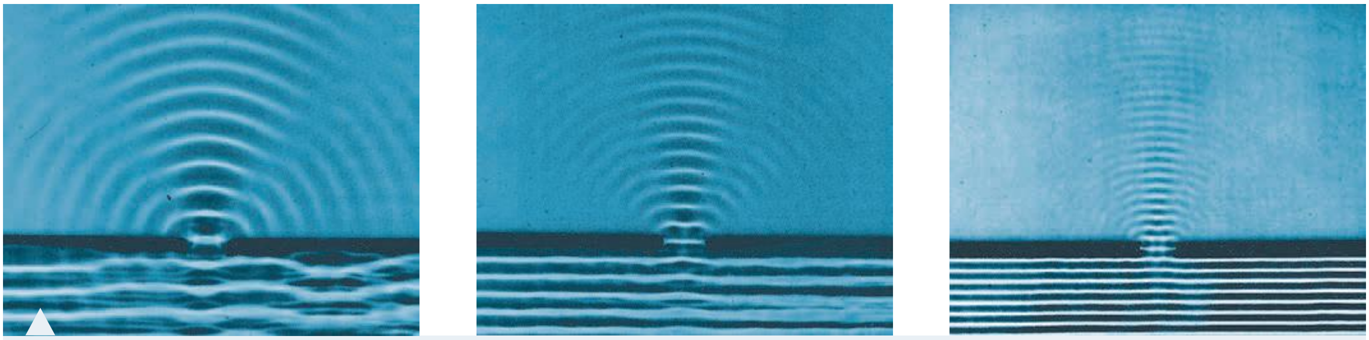

FIGURE 18.6.2 Diffraction of water waves – a model for light diffraction. Waves spread into the region beyond the gap. The spread of the central maximum decreases as the wavelength becomes similar to, or smaller than the gap width.

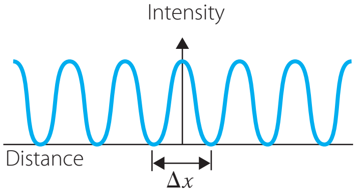

FIGURE 18.6.3 Intensity vs distance from centre for a double-slit interference pattern. Δx is the distance between dark bands.

Young's double-slit experiment

When a narrow beam of light strikes two slits, the slits produce diffraction patterns, which then overlap. A pattern of bright and dark patches is noticeable on a screen some distance away. Unlike a single slit, the central maximum, while still the brightest, is less wide.

The double-slit phenomenon can be explained as a wave interference effect.

The light from the original source spreads out as waves into the region behind the slits. Each wavefront that strikes the double slit is sampled by the slits. The slits act effectively as new sources of circular waves. A plane wave crest becomes a circular crest at each slit. A plane wave trough becomes a circular trough at each slit. Because the waves from these new sources come from the same original wavefront, they overlap. Waves that are in phase have peaks and troughs occurring at the same time. Hence a peak is incident on, and leaves from, each slit simultaneously. The troughs coming behind these peaks do the same, and so on. This happens for all wavefronts, even if they were emitted from the original source in a random way. This leads to the formation of an interference pattern on a screen that does not change with time.

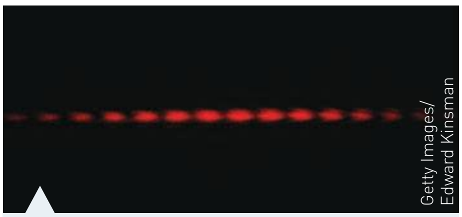

FIGURE 18.6.4 A laser beam produces an interference pattern when passed through a double-slit arrangement.

INQUIRING FURTHER

Thomas Young was a true child prodigy who made significant advancements in our understanding of light from a physical and biological view point. Investigate his life and examine how his discoveries have resulted in significant technological and medical improvements.

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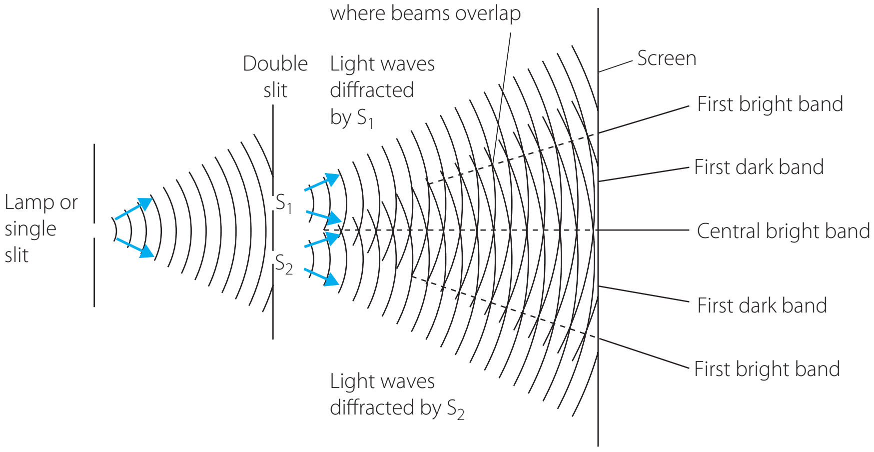

FIGURE 18.6.5 Waves from a source producing waves randomly are incident on a double-slit arrangement. Each wavefront is sampled simultaneously at both slits, leading to the formation of a consistent pattern of maxima and minima.

SYLLABUS LINK

The double-slit experiment is considered to be the defining evidence of something having wave-like properties. We will revisit the experiment when we discuss matter waves in Chapter 12 of *Nelson QScience Physics Units 3 & 4*.

A wave train may be considered as a series of positive crests and negative troughs. If two crests or two troughs overlap, they increase the amplitude. This is called constructive interference. Destructive interference occurs when a crest and a trough overlap.

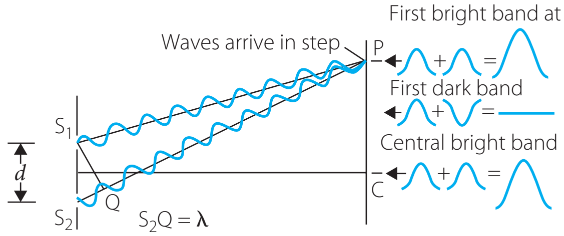

FIGURE 18.6.6 Path differences lead to maxima and minima. The formation of the first bright band is shown.

Constructive interference

Everywhere along the perpendicular line between the slits, crests and troughs that have been produced from the same wavefront will overlap. This gives rise to the central maximum. Other maxima occur as a result of constructive overlap between crests and troughs that have been emitted earlier at one slit relative to the other slit. When the path difference between these waves is a whole number of wavelengths, there will be constructive interference.

For constructive interference, path difference $= n\lambda$, where $n = 1, 2, 3, \ldots$

Destructive interference

In between these maxima there are minima, also called nodes or nodal points, where crests produced earlier at one slit overlap with troughs produced later. In these cases, the path difference is an odd number of half wavelengths.

For destructive interference, path difference $= (2n - 1)\frac{\lambda}{2}$, where $n = 1, 2, 3, \ldots$

SECTION REVIEW 18.6

REMEMBERING

1 Draw a diagram to show the intensity of light on a screen when:

a light diffracts through a single slit.

b light interferes after travelling through a double-slit arrangement.

2 Write down the path difference relationship and the sequence of values for n for:

a constructive interference. **b** destructive interference.

UNDERSTANDING

3 Explain what happens to the diffraction effect when the width of the obstruction becomes greater.

APPLYING

4 If the path difference to the second dark band away from the central maximum of a Young's double-slit experiment is 750 nm, what is the wavelength associated with the source of light used?

CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 Define the following terms.
- **a** The ray model
- **b** The wave model
- **c** The particle model
- **d** Photon
- **e** Electromagnetic radiation
- **f** Reflection
- **g** Refraction
- **h** Refrangibility
- **i** Diffraction

2 State the law of reflection.

3 Explain why light cannot be modelled as a mechanical wave.

CATEGORY QUESTIONS

4 Explain what happens to a light wave travelling in air when it is incident on a transparent object. Give your explanation in terms of wave velocity, frequency, wavelength, angle of incidence, angle of reflection and angle of refraction.

5 Compare what happens to white light when it refracts through a transparent object with what happens to a light wave of a single frequency refracting through the same object.

6 Explain how the refraction of light is used by the lens of the eye to focus images onto the retina.

7 Explain why light is said to obey the wave–particle duality.

8 Give an example of light behaving as a wave.

9 Give an example of light behaving as a particle.

ELABORATION QUESTIONS

10 What effect does the refraction of light have on the Sun when it is near the horizon?

11 How does the inability of the muscles of the eye to maintain the shape of the lens lead to the conditions of short and long sightedness?

12 Explain what results you would expect to see in the double-slit experiment if light only obeyed the particle model.

13 Do you think that diffraction and the effects of interference confirm that light is a wave?

EVIDENCE QUESTIONS

14 What evidence can you find that inadequate actions by eye muscles lead to short and long sightedness?

15 The theory of quantum physics also relies upon wave–particle duality to describe the physical universe and to explain that matter sometimes exhibits wave-like properties. How does this affect your understanding of the behaviour of light?

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END-OF-CHAPTER EXAM

End-of-chapter test

PHYSICS

1 The absorption and emission of photons of light is a feature of the:

A ray model of light.

B wave model of light.

C particle model of light.

D corpuscular model of light.

2 Which of the following is an example of a non-luminous material?

A The computer screen

B The Sun

C The Moon

D A firefly

3 In the electromagnetic wave model, light is modelled as a:

A three-dimensional transverse wave.

B two-dimensional transverse wave.

C three-dimensional longitudinal wave.

D two-dimensional longitudinal wave.

4 Which of the following options would not impact on the intensity of a light wave measured at a distance r from a point source of light?

A The power of the source

B The distance of the measuring point from the source

C The wavelength of light emitted from the source

D The size of the area in which the intensity is measured

5 The inability to see a clearly reflected image on the surface of an opaque object is due to:

A specular reflection.

B diffuse reflection.

C total internal reflection.

D regular reflection.

6 What is another name given to the fundamental vibrational mode of an object?

7 Is the reflection that you see in a plane mirror a real or a virtual image?

8 Explain the phenomenon of chromatic dispersion.

9 Describe what happens to the frequency, velocity and wavelength of a light wave when it undergoes refraction away from the normal.

10 If the intensity of light is 400 W m^{-2} at a certain distance from a point source of light, calculate its intensity at a distance that is three times further from the source.

11 Calculate the amount of time it would take a sound wave travelling at 343 m s^{-1} to cover the distance travelled by light in 0.01 s.

12 Light travelling in air (n_{air} = 1.00) enters a glass block (n_{glass} = 1.49) at an angle of incidence of 30°.

a What is the angle of refraction in the glass?

b The glass block is now immersed in oil (n_{oil} = 1.28). Does the angle of refraction get larger or smaller? Support your answer with calculations.

13 If two light rays of 456 nm exit simultaneously from the slits in a double-slit experiment, calculate the minimum path length difference that would be needed to form a dark spot on the screen.

14 Explain how rainbows are produced on days when there is moisture in the atmosphere.

15 Explain how an interference pattern is formed on a screen set up behind a light source that is projected on a double-slit experiment.

16 Object O is placed in front of a plane mirror as shown in Figure 18.7.1.

a Construct a ray model diagram to locate the positions of the images of O as observed at L and K.

b From the point of view of an observer moving from L to K, how does the image of O move?

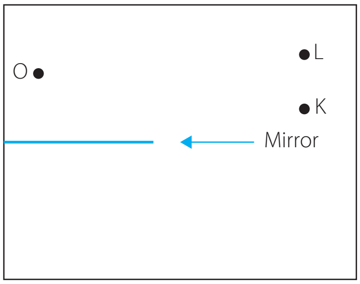


FIGURE 18.7.1

UNITS 1 & 2 PRACTICE EXAM

MULTIPLE-CHOICE QUESTIONS

QUESTION 1

Two assumptions of the kinetic particle model are that:

A all matter is made of kinetic and potential energy particles, and collisions between particles are elastic.

B all matter is made of small elastic particles, and potential energy depends on the size of the particles.

C all matter is made of small particles in constant motion that are sometimes bumping into each other, and potential energy depends on the distance between particles.

D all matter is made of small particles that lose some kinetic energy when they bump into each other, and potential energy is stored between the particles.

QUESTION 2

The specific heat capacity of a substance is:

A the amount of heat energy needed per unit mass to change state.

B the amount of heat energy needed per unit mass to change the kelvin temperature from melting point to boiling point.

C the amount of heat energy needed per unit mass to change the Celsius temperature from the solid state to the liquid state, and from the liquid state to the gaseous state.

D the amount of heat energy needed per unit mass to change the temperature by 1 K.

QUESTION 3

Why is there no change of temperature during a change of state?

A The heat added is all going into internal energy changes but not linear kinetic energy changes.

B The heat added is all going into linear kinetic energy changes but not potential energy changes.

C The heat added is all going into internal and linear kinetic energy changes but not potential energy changes.

D The heat added is all going into linear kinetic energy and potential energy changes but not internal energy changes.

QUESTION 4

750 g of copper is brought to melting point. How much energy is needed to melt all the copper to liquid? The latent heat of copper is 205 kJ kg^{-1}.

A 2.73 MJ

B 273 kJ

C 1.54 MJ

D 154 kJ

QUESTION 5

The two main forms of radiation are:

A cosmic radiation and ionising radiation.

B non-ionising radiation and background radiation.

C electromagnetic radiation and cosmic radiation.

D ionising radiation and non-ionising radiation.

QUESTION 6

The nuclide $^{234}_{90}Th$ undergoes beta particle decay. Which of the following is the daughter nuclide?

A $^{226}_{88}Rn$

B $^{230}_{90}Th$

C $^{234}_{91}Pa$

D $^{238}_{92}U$

QUESTION 7

In order to form radon $^{222}_{86}Rn$, radium $^{226}_{88}Ra$ undergoes nuclear decay. What is the other product of this reaction?

A An alpha particle

B A beta particle

C A gamma ray

D None of the above

QUESTION 8

The initial mass of a sample isotope was found to be 32 g. After 12 days, the sample was again measured, and only 2 g of the original isotope remained. What is the half-life of the isotope?

A 6 days

B 4 days

C 3 days

D 1.5 days

QUESTION 9

What is the conventional current in a wire in a circuit?

A The flow of electrons from positive to negative

B The flow of negative charges from negative to positive

C The flow of protons from negative to positive

D The flow of positive charges from positive to negative

QUESTION 10

Compared with an ohmic device, a non-ohmic device has:

A a constant resistance.

B a constant energy.

C a non-constant resistance.

D a non-constant energy.

QUESTION 11

For a velocity versus time graph, the area and the gradient represent, respectively:

A acceleration and displacement.

B displacement and velocity.

C speed and distance.

D displacement and acceleration.

QUESTION 12

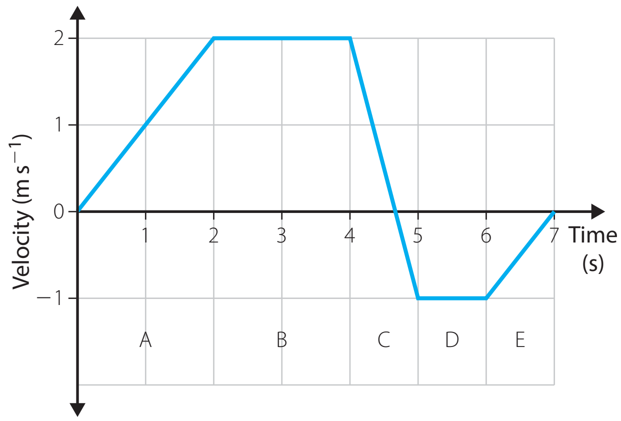
The graph below represents the velocity of an object travelling in a straight line for a short period of time. Identify the sections in which the object is undergoing acceleration.

A A and C

B A and E

C A, C and E

D B and D



QUESTION 13

Which of the following statements is correct about a collision between two bodies, P and Q?

A Forces act in pairs. The forces are equal but oppositely directed. The vector sum of the force on P and Q is zero.

B Forces act in pairs. The forces are equal but oppositely directed. The forces cannot be added to make a vector sum on either P or Q.

C For every action there is an equal and opposite reaction. The vector sum of the force on P is zero.

D For every action there is an equal and opposite reaction. The vector sum of the force on Q is zero.

QUESTION 14

For force–displacement *F*–*s* and force–time *F*–*t* graphs, the areas under the graphs represent, respectively:

A impulse and momentum.

B work and energy.

C work done and change in momentum (impulse).

D momentum change and energy transfer.

QUESTION 15

Which of the following does the greatest amount of work?

A An 11 g snail crawling a distance of 9.2 cm.

B A 1200 kg car driving a distance of 10 m up a 5.5° slope.

C A crane pulling a 190 kg basket 8.5 m vertically up.

D A 60 kg gymnast increasing the height of their centre of mass by 38 cm above the top of parallel bars.

QUESTION 16

For a sound wave, wavelength and period are, respectively:

A the length between a compression and the next rarefaction, and time for the wave to go from compression to rarefaction.

B the length between a compression and the next rarefaction, and time for the wave to go from compression to compression.

C the length between a compression and the next compression, and time for the wave to go from compression to rarefaction.

D the length between a rarefaction and the next rarefaction, and time for the wave to go from rarefaction to the next rarefaction.

QUESTION 17

A series of waves travels towards a beach. The crest of each wave has a height of 1.45 m above the sand. The trough of each wave is 1.35 m above the sand. What is the amplitude of the wave?

A 20 cm

B 15 cm

C 10 cm

D 5.0 cm

QUESTION 18

Rays of light that travel parallel to the axis are brought to a real focus in:

A convex lenses but not convex mirrors.

B convex lenses and convex mirrors.

C concave lenses but not concave mirrors.

D concave lenses and concave mirrors.

QUESTION 19

Which formula is applicable for determining the wavelength of sound from a pipe closed at one end?

A $\lambda = (2n+1)\frac{L}{2}$

B $\lambda = (2n-1)\frac{L}{4}$

C $L = (2n-1)\frac{\lambda}{4}$

D $L = (2n+1)\frac{\lambda}{2}$

QUESTION 20

A 2.4 cm object is 4.0 cm from a converging lens of focal length 9.0 cm. The nature, position and magnitude of the image are, respectively:

A virtual, 11.3 cm and 6.8 cm.

B virtual, $^{-}7.2$ cm and 4.32 cm.

C real, 11.3 cm and 6.8 cm.

D real, 7.2 cm and 4.32 cm.

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SHORT-RESPONSE QUESTIONS

QUESTION 1
State the term used for the amount of heat energy needed per unit mass to change the temperature by 1 K.

QUESTION 2
How much energy is needed to raise the temperature of 200 mL of milk from 5°C to 50°C? Assume that the specific heat capacity of milk is $4010\ \text{J kg}^{-1}\ \text{K}^{-1}$.

QUESTION 3
State the general form of the alpha particle nuclear decay equation.

QUESTION 4
How long will it take 4.0 mg of technetium-99m, with a half-life of 6.0 h, to decay to 20 μg?

QUESTION 5
State the term for the flow of positive charges from positive to negative terminal within an electric circuit.

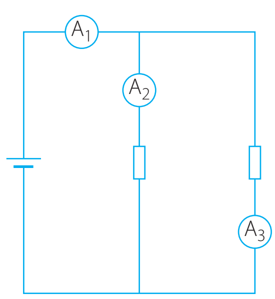
QUESTION 6
Explain why is there no change of temperature during a change of state.

QUESTION 7
When a pure substance is heated, its temperature is directly proportional to the energy transferred from the source provided that three assumptions are maintained. State these three assumptions.

QUESTION 8
Describe the structure of an atom.

QUESTION 9
One possible daughter nuclide from the fission of U-235 is $^{141}_{56}\text{Ba}$. This nuclide will later undergo decay to form $^{141}_{57}\text{La}$. Determine the other product of this decay and write the complete nuclear decay equation.

QUESTION 10
In the electrical circuit below, the readings for A_1 and A_2 are 250 mA and 100 mA, respectively. Determine the reading for ammeter A_3 and state the law used to find this value.



QUESTION 11

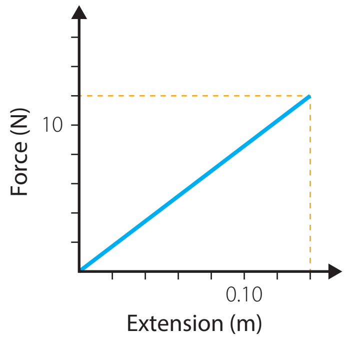
State the linear kinematic formula used to determine a constant acceleration, *a*.

QUESTION 12

What average net force must be applied to a 3.5 kg skateboard moving at $5.0\,\text{m s}^{-1}$ to bring it to rest over a displacement of 0.50 m?

QUESTION 13

The graph below represents the force applied to a light spring and the resultant extension. Determine the value of the spring constant.



QUESTION 14

A cricket ball of mass 160 g is dropped from a second-floor window that is 5.9 m above the ground. Its drop is timed and is found to take 1.1 s to reach the ground. Determine the impulse that the ball receives as it falls.

QUESTION 15

If the intensity of light is $400\,\text{W m}^{-2}$ at a certain distance from a point source of light, calculate its intensity at a distance which is three times further from the source.

QUESTION 16

A cyclist begins a short journey pedalling at an average speed of $8.0\,\text{m s}^{-1}$ along a straight road. She tires after 8.0 minutes and drops her average speed to $6.0\,\text{m s}^{-1}$, taking a further 17.0 min to complete the trip. Determine how far she travelled in total.

QUESTION 17

A force of 25 N is applied to a 0.125 kg ball. Its speed increases by $28\,\text{m s}^{-1}$. For how long was the force of 25 N applied to the ball?

QUESTION 18

Contrast longitudinal waves with transverse waves.

QUESTION 19

A musical note has a wavelength of 0.645 m. If the speed of sound is $340\,\text{m s}^{-1}$, determine the frequency of the sound wave.

QUESTION 20

Describe the nature of the image formed when an object is placed between one and two focal lengths from a concave mirror.

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COMBINATION-RESPONSE QUESTIONS

QUESTION 1

Refer to the values provided to respond.

- Specific heat capacity of water = 4200 J kg^{-1} K^{-1}
- Latent heat of vaporisation of water = 2260 kJ kg^{-1}

How much energy is needed to convert 300 mL of water at 20°C to steam at 100°C? State the individual specific heat and latent heat values as well as the sum of the heat energy required.

QUESTION 2

A steam turbine provides 4.29 GJ of heat energy to turn 1200 kg of water at 20°C into steam. Determine the final temperature of the steam.

- Specific heat capacity of liquid water = 4200 J kg^{-1} K^{-1}
- Specific heat capacity of gaseous water (steam) = 2000 J kg^{-1} K^{-1}
- Latent heat of vaporisation (water to steam) = 2260 kJ kg^{-1}

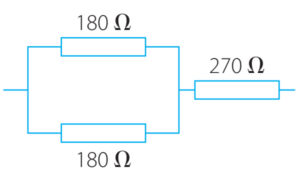
QUESTION 3

When ${}^{3}_{1}H$ (tritium) combines with ${}^{2}_{1}H$ (deuterium) in a fusion reaction, helium is produced according to the reaction: ${}^{3}_{1}H + {}^{2}_{1}H \rightarrow {}^{4}_{2}He + {}^{1}_{0}n + \gamma$

If 17.6 MeV of energy is produced, determine the mass loss (mass defect) in the reaction?

QUESTION 4

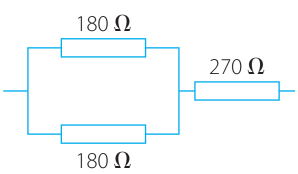
Three resistors are connected together in a combination circuit with two 180 Ω resistors in parallel and a 270 Ω resistor in series, as shown.



Determine the value of the total effective resistance.

QUESTION 5

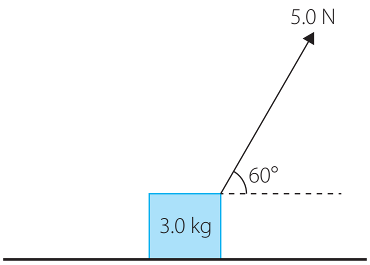
A potential difference of 12 V is applied across the combination of resistors shown in the partial circuit diagram below.



Determine the value of the current that flows in the 270 Ω resistor.

QUESTION 6

A box of mass 3.0 kg is being pulled along towards the right across a frictionless surface by a force of 5.0 N applied at an angle of 60° to the horizontal.



Determine the magnitude of the normal force acting on the box.

QUESTION 7

A 1.6×10^3 kg vehicle is travelling east at 15 m s^{-1} while a 5.5×10^3 kg truck is travelling west at 10 m s^{-1}. The car and truck collide and continue to move off as one mass stuck together.

a Calculate the initial momentum of both vehicles.

b Calculate the final momentum of the combined vehicles.

c Determine the velocity, v_{final}, of the wreckage immediately after the collision.

QUESTION 8

A guitar string has a length of 72 cm. When plucked at its centre it is found to have a fundamental frequency of 236 Hz. Use the speed of sound in air of 340 m s^{-1} to determine the wavelength of this note.

QUESTION 9

The relative refractive index across a water–diamond interface is 1.82. Use Snell's law to determine the angle of the refracted ray in the diamond, if the angle of incidence in the water is 36°.

QUESTION 10

An object is placed 20.0 cm in front of a converging lens and an inverted image that is twice the size of the object is obtained. Determine the focal length of the lens.

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CHAPTER 1: THERMAL, NUCLEAR AND ELECTRICAL PHYSICS

1.1 SECTION REVIEW

REMEMBERING

1 a Solid: fixed shape, fixed volume
  b Liquid: no fixed shape, fixed volume
  c Gas: no fixed shape, no fixed volume
2 Brownian motion: the random motion of small objects suspended in a fluid as a result of their collision with the particles of the fluid
3 Kinetic energy and potential energy
4 A displacement of the particles from their mean position as determined by their intermolecular forces

UNDERSTANDING

1 Since temperature is directly proportional to the average kinetic energy of the particles in a substance, and increase in temperature of a substance is accompanied by an increase in the average kinetic energy of the particles in that substance.
2 a Solid: The particles oscillate around a mean position, but the kinetic energy of the particles is insufficient to overcome the bonding caused by the intermolecular forces
  b Liquid: The kinetic energy of the particles is sufficient to allow them to move significantly away from their mean position and ultimately slide past one another.
  c Gas: The kinetic energy of the particles is sufficient to allow them to break entirely free from their intermolecular bonds
3 Heat always moves from a hotter object to a colder object, so as the temperature of the objects gets very close to absolute zero, there will no longer be any other object that the energy can move to and so the initial object will not be able to be cooled any further.

1.2 SECTION REVIEW QUESTIONS

REMEMBERING

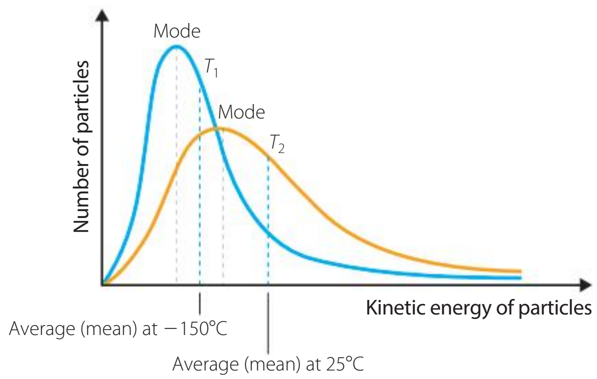
1 a The energy a particle has because of its motion
  b The energy a particle has due to its position
  c The total sum of the kinetic and potential energies of all of the particles within an object
  d A measure of the average kinetic energy of the particles in a substance
  e The transfer of thermal energy through a substance or between substances
2 The internal energy of a substance will also increase if the average internal energy is also increasing.
3 The internal energy of a substance decreases if the amount of potential energy stored in its intermolecular bonds decreases.

UNDERSTANDING

4 Chemical energy stored in the coal is transferred to heat energy during combustion; this is then transformed to kinetic and potential energy in the water as it turns to steam. The kinetic energy in the steam is transferred to kinetic energy in the rotating turbines.
5 The potential energy in a bond is at a minimum when its particles are at their mean separation, so an increase or a decrease in this length results in an increase of the potential energy stored.
6 Heat is a transfer of energy between objects, whereas temperature is a measure of the average kinetic energy of the particles in an object.
7 An increase in the internal energy of an object can be due to an increase in the kinetic energy of its particles, an increase in the potential energy stored in its bonds or both. Since temperature is a measure of the average kinetic energy of the particles of an object, it will not increase if the increase in internal energy is due to an increase in an object's potential energy.

APPLYING

8



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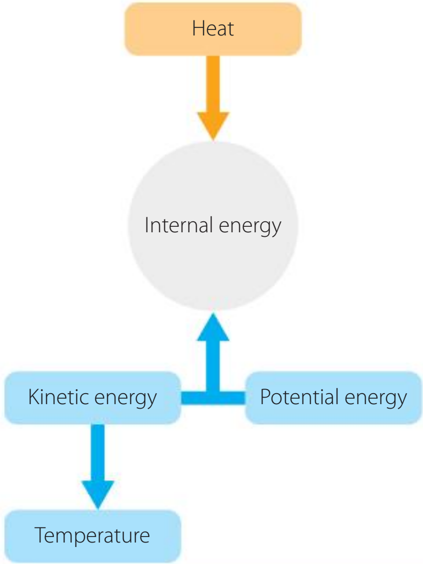


1.3 SECTION REVIEW

REMEMBERING

1 a process by which energy is transferred through the collision of atoms

b process by which energy is transferred through the bulk motion of a fluid

c The process of transferring heat energy by electromagnetic radiation.

2 Infrared – Visible – X-Ray

UNDERSTANDING

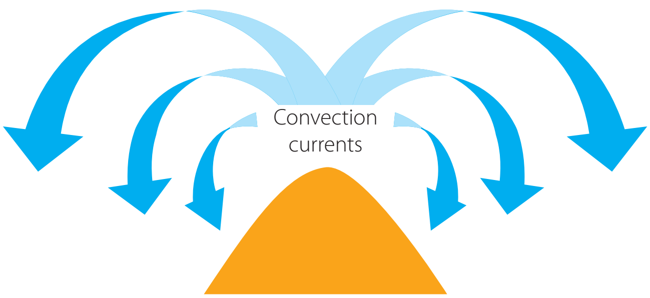
3 Copper, as with most metals, has many free electrons which can move around the sample unhindered and quickly transport kinetic energy through the sample. Wood has tightly bound electrons that are fixed in place and therefore the transfer of kinetic energy is dependent upon the movement of particles.

4 The water at the top of a body of water is exposed to radiation from the Sun and to conduction with the warmer air, whereas water further down is completely dependent upon the conduction of heat from the upper sections.

5 Heat is transferred from the Sun in the form of radiation until it comes in contact with particles in the atmosphere. Heat from these particles is transferred by either conduction or convection to other particles in the atmosphere until eventually heat is transferred from these particles to the surface of Earth by conduction.

APPLYING

6



CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 a A physical substance

b The capacity to do work

c The fundamental building block of matter

d A collection of atoms bound together by chemical bonds

e A small portion of matter

f The random motion of small objects suspended in a fluid as result of them being bombarded by the particles of the fluid

g The energy of an object due to its motion

h Energy that is stored in a system due to the configuration and interaction of the bodies within the system

i The sum of the kinetic energy of the particles in a system and the potential energy stored in a system

j A collision between two or more objects in which there is no loss of kinetic energy

k Electrostatic forces of attraction or repulsion between neighbouring particles of a substance

l A measurement of the average kinetic energy of the particles in a substance

m The transfer of thermal energy through a substance or between substances.

n The process by which energy is transferred through the collision of atoms

o The condition that occurs when there are density differences within a fluid; the density differences result in rising and falling currents

p Energy transferred across empty space; the transfer of heat by electromagnetic radiation

2 The large number of particles in any substance together with the fact that they are all constantly moving and colliding with each other means that the motion of any individual particle is impossible to calculate.

CATEGORY QUESTIONS

3 Heat is the transfer of energy between objects, whereas the temperature of an object is a measure of the average kinetic energy of the particles of that object.

4 • All matter is made up of small particles which are in constant motion

• These particles contain kinetic energy due to their motion and potential energy stored in their intermolecular bonds

• Collisions between the particles are perfectly elastic

• The particles obey classical mechanics

• The temperature of an object is proportional to the kinetic energy of its particles

5 Solid: The particles oscillate around a mean position, but the kinetic energy of the particles is insufficient to overcome the bonding caused by intermolecular forces.

Liquid: The kinetic energy of the particles is sufficient to allow them to move significantly away from their mean position and ultimately slide past one another.

Gas: The kinetic energy of the particles is sufficient to allow them to break entirely free from their intermolecular bonds.

6 Different materials have different intermolecular bond strengths that help to keep the particles in place. In a substance with a weaker intermolecular bond strength, an addition of heat would allow the particles to move more freely and therefore collide with more particles, which would spread the heat quickly. A more tightly bound material would impede the freedom of the particles, reducing the amount of collisions and therefore reducing the speed of heat transfer.

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7 Different temperatures emit different wavelengths of light. Astronomers are able to estimate the temperature of distant objects by comparing the wavelengths of incoming light to the temperatures that would create them.

ELABORATION QUESTIONS

8 The kinetic particle model explains that heat is the transfer of thermal energy due to either convection, conduction or radiation, while temperature is a measure of the average kinetic energy of the particle in a substance.

9 Even though the total kinetic energy of an object is constant at a fixed temperature, and therefore, so is the average kinetic energy of the particles, the individual kinetic energy of each particle is constantly changing because the particles are constantly undergoing collisions with each other. Therefore, there is no way to know the temperature of an individual particle.

10 If the collisions were not elastic, there would be a loss of kinetic energy during the collisions and therefore the total kinetic energy of the object and the average kinetic energy of the object's particles would decrease over time. This means that the temperature of the object would also decrease with time.

11 The most energetic particles are those that have a kinetic energy above the average kinetic energy of the particles within the substance undergoing cooling. By removing these particles, the scientists are effectively reducing the average kinetic energy of the particles within the object and therefore cooling it down.

EVIDENCE QUESTIONS

12 Caloric was a hypothetical fluid that carried heat from one object to another. The evidence that supported this idea included the fact that heat flows much like a fluid, while the greatest piece of evidence against it is the fact that heat can be transferred through the vacuum of space.

13 The model itself would not be greatly altered as it has been extremely successful in describing the thermodynamic behaviour of objects. The greatest changes would be in the detail that could be used to describe the expected behaviour of heat flow and temperature change of objects as collisions between particles, and the resulting energy changes could be accurately predicted.

14 Einstein's explanation of Brownian motion as being the random motion of particles suspended in fluid due to their collision with smaller particles of the fluid supported the atomic model in that it gave direct evidence of atomic particles.

END-OF-CHAPTER EXAM

1 A

2 C

3 B

4 D

5 B

6 Heat

7 Increasing

8 Internal energy

9 Radiation

10 Thermodynamics

11 The random motion of small objects suspended in a fluid as a result of them being bombarded by the particles of the fluid.

12 The addition of heat will cause an increase in the internal energy of the substance. This could be due to an increase in the total kinetic energy of the substance, which would also cause an increase in the average kinetic energy of the particles of that substance and therefore its temperature, or it could be due to an increase in the potential energy stored in the intermolecular bonds of the substance.

13 The temperature of a substance is directly proportional to the average kinetic energy of the particles of a substance.

14 Heat is the transfer of energy between substances while temperature is a measure of the average kinetic energy of the particles of that substance.

15 the process by which energy is transferred through the collision of atoms

16 When heat is added to a substance, the energy can be transformed into either an increased velocity of the particles or to a change in the distance between particles. An increase in the velocity of the particles would mean an increase in the amount of kinetic energy of the particles, while a change in the distance between the particles would mean an increase in the amount of potential energy stored in the intermolecular bonds.

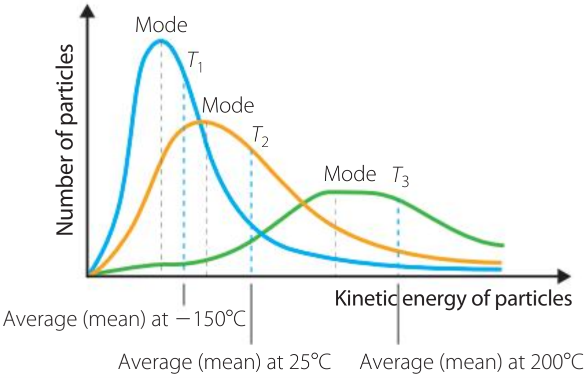
17 Heat convection occurs due to one area of a fluid being warmer than the rest of the substance. The heat conduction occurring in this region causes the hotter, more energetic particles to move out into the areas containing the cooler, less energetic particles. In this way, heat is transferred throughout the substance.

18 Solid: The particles oscillate around a mean distance, but the kinetic energy of the particles is insufficient to overcome the bonding caused by the intermolecular forces.

Liquid: The kinetic energy of the particles is sufficient to allow them to move away from their mean position and store energy on the form of potential energy. The distance between the particles increases and allows them to slide past one another.

Gas: The kinetic energy of the particles is sufficient to allow them to break entirely free from their intermolecular bonds, which allows the distance between particles to increase greatly.

19



CHAPTER 2: TEMPERATURE AND SPECIFIC HEAT CAPACITY

2.1 SECTION REVIEW

REMEMBERING

1 0 K; The coldest of all temperatures, where the motion of particles ceases. Also, since temperature is proportional to kinetic energy, where the temperature is zero.

2 It is important to have a universal temperature scale so that findings, calculations and observations can be clearly communicated.

UNDERSTANDING

3 There are no negative values, which means that it is convenient for measuring very low temperatures and it is simpler to compare different temperatures

4 a Qualitative

b Quantitative

c Quantitative

d Qualitative

e Quantitative

APPLYING

5 $T_k = T_C + 273$

Use the temperature conversion formula

$T_k = 54 + 273$

Substitute known values

$T_k = 327$

Calculate answer

$T_k = 300\,K$

Give answer to correct number of significant digits and with correct unit

6 $T_k = T_C + 273$

Use the temperature conversion formula

$T_k - 273 = T_C$

Subtract 273 from both sides

$T_C = T_k - 273$

Make T_C the subject of the formula

ANALYSING

7 • Most people are unfamiliar with the Kelvin scale

• Common everyday temperatures are relatively high

2.2 SECTION REVIEW

REMEMBERING

1 A device that measures temperature or a temperature gradient.

2 They both use the variation in resistivity of a material with temperature.

UNDERSTANDING

3 Reacts to a temperature change in a predictable and measurable way

ANALYSING

4 Railway lines have expansion joints to prevent them from buckling during temperature changes.

2.4 SECTION REVIEW

REMEMBERING

1 Joule and calorie. Joule is the SI unit.

2 Heat is the transfer of thermal energy.

UNDERSTANDING

3 Temperature does not flow between objects. Rather, heat flows from the hotter object to the colder object, resulting in a decrease in temperature of the hotter object and an increase in temperature of the colder object

4 When electricity flows through the resistors in the heater, the particles in the resistor increase in kinetic energy and therefore temperature. These particles collide with air particles and transfer their kinetic energy through conduction. After the collisions, the air particles have a greater amount of kinetic energy than before the collision and the resistor particles have less kinetic energy than before. The air particles then undergo convection and collide with other air particles to increase their kinetic energy.

5 The cool air particles coming out of the air conditioner collide with the warmer air particles in the room. After this collision, the cooler air particles increase their kinetic energy and the warmer particles decrease their kinetic energy. In this way, the average kinetic energy and therefore the temperature of the air particles in the room decreases.

APPLYING

6 $\text{Energy (J)} = 150\,\text{cal} \times \dfrac{4.186\,\text{J}}{1\,\text{cal}}$

Apply conversion factor (1 cal = 4.186 J)

Energy (J) = 627.9 J

Calculate answer

Energy (J) = 630 J

Give answer to correct number of significant figures

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7 Energy (cal) = $1400\,\text{J} \times \frac{1\,\text{cal}}{4.186\,\text{J}}$

Apply conversion factor (1 cal = 4.186 J)

Energy (cal) = 334.4 cal

Calculate answer

Energy (cal) = 330 cal

Give answer to correct number of significant figures

8 Power = $\frac{\text{Energy}}{\text{Time}}$

Apply power formula

Energy = Power × Time

Rearrange formula for required value of energy

Energy = 200 W × 2 min

Insert known values

Energy = $200\,\text{J}\,\text{s}^{-1} \times 2\,\text{min}$

Change watts to base units ($1\,\text{W} = 1\,\text{J}\,\text{s}^{-1}$)

Energy = $200\,\text{J}\,\text{s}^{-1} \times 120\,\text{sec}$

Apply conversion factor (1 min = 60 s) to change time to SI units

Energy = 24 000 J

Calculate answer

Energy = 20 000 J

Give answer to correct number of significant figures

2.5 SECTION REVIEW

REMEMBERING

1 1 kg of iron requires 450 J of heat to be added to it to increase its temperature by 1°C

2 Since the change in temperature of an object is proportional to the amount of heat added to it when the mass is kept the same, a doubling of the amount of heat will increase its temperature by twice as much. The object will therefore have a temperature increase of 2°C.

3 Since the amount of heat required to increase the temperature of an object is proportional to the mass, a halving in the mass will require half as much heat to increase its temperature by the same amount. The substance will therefore require 200 J of heat to increase its temperature.

UNDERSTANDING

4 $Q = mc\Delta T$

Apply the specific heat equation

$c = \frac{Q}{m\Delta T}$

Rearrange the formula to make c the subject

$c = \frac{\text{J}}{\text{kg}\,°\text{C}}$

Insert the units

The units of the specific heat capacity are therefore: $\text{J}\,\text{kg}^{-1}\,°\text{C}^{-1}$

5 Steam: $2000\,\text{J}\,\text{kg}^{-1}\,\text{K}^{-1}$

Ice: $2100\,\text{J}\,\text{kg}^{-1}\,\text{K}^{-1}$

Water: $4180\,\text{J}\,\text{kg}^{-1}\,\text{K}^{-1}$

ANALYSING

6 Water has a high specific heat capacity, meaning that it requires a large amount of heat to increase its temperature by 1°C. This means that it is useful as a heat sink to absorb significant amount of heat to be transported in or out of an area needing cooling or heating.

2.6 SECTION REVIEW

REMEMBERING

1 A calorimeter is a highly insulated container that prevents heat energy being lost to the environment and enables the measurement of a heat change.

2 a J

b kg

c $\text{J}\,\text{kg}^{-1}\,\text{K}^{-1}$

d K or °C

UNDERSTANDING

3 $Q = mc\Delta T$

Apply the specific heat equation

$\Delta T = \frac{Q}{mc}$

Rearrange the formula to make ΔT the subject

$T_f - T_i = \frac{Q}{mc}$

Expand ΔT to $T_f - T_i$

$T_f = \frac{Q}{mc} + T_i$

Add T_i to both sides

4 Since the power of a heating element is proportional to the voltage ($P = VI$), a doubling of the current will result in a doubling of the power

APPLYING

5 $Q = mc\Delta T$

Apply the specific heat equation

$Q = 0.3\,\text{kg} \times 2400\,\text{J}\,\text{kg}\,°\text{C}^{-1} \times 15°\text{C}$

Insert known values in SI units

$Q = 10\,800\,\text{J}$

Calculate the answer to the correct number of significant figures

6 $Q = mc\Delta T$

Apply the specific heat equation

$\Delta T = \frac{Q}{mc}$

Rearrange the formula to make ΔT the subject

$T_f - T_i = \frac{Q}{mc}$

Expand ΔT to $T_f - T_i$

$T_f = \frac{Q}{mc} + T_i$

Add T_i to both sides

$$T_f = \frac{2500\,\text{J}}{2\,\text{kg} \times 800\,\text{J kg}^{-1}\,°\text{C}} + 25°\text{C}$$

Insert known values

$T_f = 26.5625°\text{C}$

Calculate the answer

$T_f = 27°\text{C}$

Give the answer to the correct number of significant figures

7 $Q = mc\Delta T$

Apply the specific heat equation

$$\Delta T = \frac{Q}{mc}$$

Rearrange the formula to make ΔT the subject

$$T_f - T_i = \frac{Q}{mc}$$

Expand ΔT to $T_f - T_i$

$$T_f = \frac{Q}{mc} + T_i \quad (1)$$

Add T_i to both sides

Call this equation (1)

$$P = \frac{Q}{t}$$

Apply the power equation

$Q = P \times t$

Rearrange the equation to make Q the subject

$Q = (IV) \times t$

Insert the power as a function of voltage and current equation $P = IV$ to the equation

$$Q = 5\,\text{A} \times 1.5\,\text{V} \times 30\,\text{min} \times \frac{60\,\text{s}}{\text{min}}$$

Insert known values in standard SI form

$Q = 13\,500\,\text{J}$ (2)

Calculate the amount of heat added and call this equation (2)

$$T_f = \frac{13\,500\,\text{J}}{mc} + T_i$$

Insert equation (2) into equation (1)

$$T_f = \frac{13\,500\,\text{J}}{0.2\,\text{kg} \times 130\,\text{J kg}^{-1}\,°\text{C}^{-1}} + 25°\text{C}$$

Insert known values

$T_f = 544.2307692°\text{C}$

Calculate the answer

$T_f = 540°\text{C}$

Give the answer to the correct number of significant figures

CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 a Thermometer: a device that measures temperature or a temperature gradient.

b Absolute zero: the theoretical lowest possible temperature; −273.15°C on the Celsius scale or 0 K on the absolute or Kelvin scale.

c Diffusion: The spontaneous movement of substances of energies from areas of high concentration to areas of low concentration.

d Specific heat capacity: the amount of energy required to increase the temperature of 1 kg by 1°C (or K) of a substance without a change of phase.

e Heat sink: an object or material that moderates the temperature of its surroundings due to its large specific heat capacity.

2 a The freezing point of water at 0°C the boiling point of water at 100°C.

b The freezing point of water at 273 K, the boiling point of water at 373 K and absolute zero at 0 K.

3 An addition of heat causes the average kinetic energy of the particles in a substance to increase. Because the temperature of a substance is proportional to the average kinetic energy of the particles making up the substance, the temperature of the object will also increase.

4 The factors affecting the size of the temperature change of an object when heat is added include its mass and its specific heat capacity.

CATEGORY QUESTIONS

5 Two requirements for a useful temperature scale are two or more reference temperatures and a scale of increments between them.

6 Answers will vary but should include any three of the following:

- coefficient of expansion
- electrical resistance at different temperatures
- colour at different temperatures
- electromagnetic radiation emitted.

7 The specific heat capacity of a substance represents the amount of energy required to increase the temperature of 1 kg of the substance by 1°C. Therefore, a substance with a higher specific heat capacity requires more energy to increase its temperature.

8 Answers will vary and may include any of the following:

- density
- chemical composition
- strength of intermolecular bonding
- type of material
- number of free electrons.

ELABORATION QUESTIONS

9 The centigrade scale is still in wide use because it is familiar. Common everyday temperatures are represented from 0°C to 100°C.

10 Answers will vary but should all be due to a decrease in its effectiveness as a heat sink. Answers may include:

- effect on climate
- effect on physiology
- effect on energy storage.

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EVIDENCE QUESTIONS

11 The universal adaption of the Kelvin scale would be useful because it would allow for a single measure of temperature. The Kelvin scale is the most useful and makes logical sense to adopt it. People who are accustomed to the Fahrenheit scale would have more difficulty with the adjustment because the conversion from Fahrenheit to Kelvin is more complex mathematically than the conversion from Celsius to Kelvin.

12 Answers will vary depending on research conducted.

END-OF-CHAPTER EXAM

1 C

2 D

3 A

4 D

5 B

6 D

7 Equal

8 The resistivity

9 Diffusion

10 An object or material that moderates the temperature of its surroundings due to its large specific heat capacity.

11 A calorimeter is used to investigate the thermodynamic properties of a substance by preventing any heat loss to the surroundings.

12 Heat will always move from a hotter object to a colder object.

13 $Q = mc\Delta T$

Apply the specific heat equation

$Q = 0.45\,\text{kg} \times 670\,\text{J kg–1}\,°\text{C}^{-1} \times (25°\text{C} - 675°\text{C})$

Insert known values in SI units

$Q = -195\,975\,\text{J}$

Calculate the answer

The heat lost is equal to 2.0×10^5 J

Give the answer to the correct number of significant figures noting that a negative value for Q indicates a heat loss.

14 $Q = mc\Delta T$

Apply the specific heat equation

$\Delta T = \dfrac{Q}{mc}$

Rearrange the formula to make ΔT the subject

$T_f - T_i = \dfrac{Q}{mc}$

Expand ΔT to $T_f - T_i$

$T_f = \dfrac{Q}{mc} + T_i$

Add T_i to both sides

$T_f = \dfrac{49\,000\,\text{J}}{0.25\,\text{kg} \times 2800\,\text{J kg}^{-1}\,°\text{C}^{-1}} + 25°\text{C}$

Insert known values

$T_f = 95°\text{C}$

Calculate the answer to the correct number of significant figures

15 $Q = mc\Delta T$

Apply the specific heat equation

$c = \dfrac{Q}{m\Delta T}$

Rearrange the formula to make c the subject

$c = \dfrac{51\,094\,\text{J}}{1.8\,\text{kg} \times 33°\text{C}}$

Insert known values

$c = 860\,\text{J kg}^{-1}\,°\text{C}^{-1}$

Calculate the answer to the correct number of significant figures

16 An addition of heat causes the kinetic energy of the particles in a substance to increase. This increase in kinetic energy also increases the likelihood for collisions to occur. Since the temperature of a substance is proportional to the average kinetic energy of the particles in a substance, the temperature will also increase.

17 A watermelon is primarily composed of water but is also encased within an insulating material.

18 Water has a very high specific heat capacity, meaning that it is able to absorb a relatively high amount of heat before its temperature is increased. Such a substance is called a heat sink. This means that it will absorb heat from its surroundings and prevent huge changes in temperature.

19 $Q = mc\Delta T$

Apply the specific heat equation

$\Delta T = \dfrac{Q}{mc}$

Rearrange the formula to make ΔT the subject

$T_f - T_i = \dfrac{Q}{mc}$

Expand ΔT to $T_f - T_i$

$T_f = \dfrac{Q}{mc} + T_i \quad (1)$

Call this equation (1)

$P = \dfrac{Q}{t}$

Apply the power equation

$Q = P \times t$

Rearrange the equation to make Q the subject

$Q = (IV) \times t$

Insert the power as a function of voltage and current equation $P = IV$ to the equation

$Q = 3\,\text{A} \times 10\,\text{V} \times 10\,\text{min} \times \dfrac{60\,\text{s}}{\text{min}}$

Insert known values in standard SI form

$Q = 18\,000\,\text{J} \quad (2)$

Calculate the amount of heat added and call this equation (2)

$T_f = \dfrac{18\,000\,\text{J}}{mc} + T_i$

Insert equation (2) into equation (1)

$$T_f = \frac{18\,000\ \text{J}}{1\ \text{kg} \times 4200\ \text{J kg}^{-1}\ {}^\circ\text{C}^{-1}} + 25^\circ\text{C}$$

Insert known values

$T_f = 29.285\,714\,29^\circ\text{C}$

Calculate the answer

$T_f = 29^\circ\text{C}$

Give the answer to the correct number of significant figures

20 Since the formula relating temperature and heat added is linear $T_f = \frac{Q}{mc} + T_i$, with gradient equal to $\frac{1}{mc}$, a graph of temperature vs heat added should also have a gradient of $\frac{1}{mc}$.

From the graph:

$$\text{Gradient} = \frac{\Delta T}{\Delta Q} = \frac{28^\circ\text{C} - 26^\circ\text{C}}{700\ \text{J} - 250\ \text{J}} = \frac{1^\circ\text{C}}{225\ \text{J}}$$

Since:

$$\text{Gradient} = \frac{1}{mc}$$

Gradient from the formula $T_f = \frac{Q}{mc} + T_i$

$$c = \frac{1}{m \times \text{gradient}}$$

Rearrange the formula for c

$$c = \frac{1}{0.5\ \text{kg} \times \frac{1^\circ\text{C}}{225\ \text{J}}}$$

Insert known values

$c = 450\ \text{J kg}^{-1}\ {}^\circ\text{C}^{-1}$

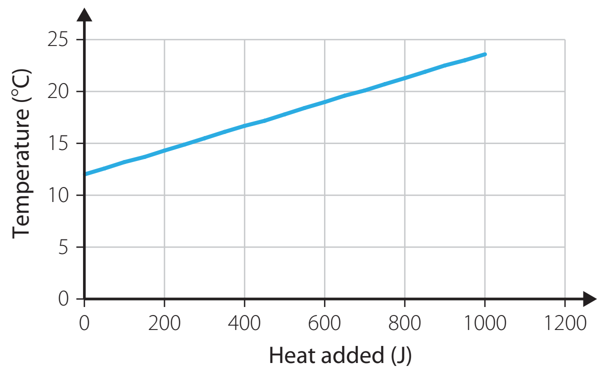
Calculate the answer

From Table 2.5.1, it is likely the substance is iron since it has a specific heat capacity of $450\ \text{J kg}^{-1}\ {}^\circ\text{C}^{-1}$.

21 The first step is to calculate the heat added at each time step. This can be done by rearranging the power formula $\left(P = \frac{Q}{t}\right)$ to give $Q = Pt$. This is included as the extra column of the table:

TIME (S)	HEAT ADDED (J)	TEMPERATURE (°C)
0	0	12
10	50	12.6
20	100	13.2
30	150	13.7
40	200	14.3
50	250	14.9
60	300	15.5
70	350	16.1
80	400	16.7
90	450	17.2
100	500	17.8
110	550	18.4
120	600	19
130	650	19.6
140	700	20.1
150	750	20.7
160	800	21.3
170	850	21.9
180	900	22.5
190	950	23
200	1000	23.6

The next step involves graphing temperature vs heat added:



As can be seen in the graph this is linear with a gradient of $0.0116^\circ\text{C J}^{-1}$.

This graph can be related to the formula $T_f = \frac{Q}{mc} + T_i$, with gradient equal to $\frac{1}{mc}$.

Therefore:

$$\text{Gradient} = \frac{1}{mc}$$

$$c = \frac{1}{m \times \text{gradient}}$$

Rearrange formula for c

$$c = \frac{1}{0.25\ \text{kg} \times 0.0116^\circ\text{C J}^{-1}}$$

Insert known values

$c = 345\ \text{J kg}^{-1}\ {}^\circ\text{C}^{-1}$

Calculate the answer

CHAPTER 3: PHASE CHANGES AND LATENT HEAT

3.1 SECTION REVIEW

REMEMBERING

1 Vaporisation is the phase change from liquid to gas at its boiling point, whereas vaporisation is the process in which some of the particles with high kinetic energy escape the surface of a liquid at a temperature below its boiling point. Vaporisation does not involve any change in temperature, whereas during evaporation, the loss of the most energetic particles results in a decrease in the average kinetic energy and therefore the temperature of the substance.

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2 B, D, C, A

UNDERSTANDING

3 During any phase change, the addition of heat results in energy being stored as potential energy by the movement of particles away from the mean position of their intermolecular bonds.

4 The constant linear slope of a heating curve in between phase changes indicates a constant increase in temperature.

5 The horizontal lines on a heating curve during a phase change indicate that there is no change in temperature.

ANALYSING

6 a 1500°C

b 2800°C

3.2 SECTION REVIEW

REMEMBERING

1 a the heat required to change the state of a substance at its boiling point or melting point without a change in temperature; unit: J kg^{-1}

b the heat required to change the state of 1 kg of a substance from a solid to a liquid without a change in temperature

c the heat required to change the state of 1 kg of a substance from a liquid to a gas without a change in temperature

UNDERSTANDING

2 Alcohol, lead, water, silver, copper, iron, aluminium. This table suggests that it would take 2260 kJ of heat to vaporise 1 kg of water and more than 4.5 times more heat, 10 500 kJ, to vaporise 1 kg of aluminium.

3 Since the amount of heat released is directly proportional to the mass of a substance, there would be three times as much heat, or 615 kJ released when 3.0 kg of liquid copper solidifies.

3.3 SECTION REVIEW

REMEMBERING

1 a Joules, J

b Kilograms, kg

c Joules or kilojoules per kilogram, J kg^{-1} or kJ kg^{-1}

2 a Latent heat of fusion

b Latent heat of vaporisation

c Latent heat of fusion

d Latent heat of vaporisation

APPLYING

3 $Q = mL_f$

Apply the latent heat of fusion formula

$Q = 0.33\,\text{kg} \times 105\,\text{kJ kg}^{-1}$

Insert known values

$Q = 34.65\,\text{kJ}$

Calculate the answer

$Q = 35\,\text{kJ}$

Give the answer to the correct number of significant figures

4 $Q = mL_v$

Apply the latent heat of vaporisation formula

$L_v = \dfrac{Q}{m}$

Rearrange to make L_v the subject

$L_v = \dfrac{52.8\,\text{kcal}}{160\,\text{g}}$

Insert known values

$L_v = \dfrac{52.8\,\text{kcal} \times \dfrac{4.18\,\text{kj}}{\text{kcal}}}{0.16\,\text{kg}}$

Apply conversion factors to get units into SI format

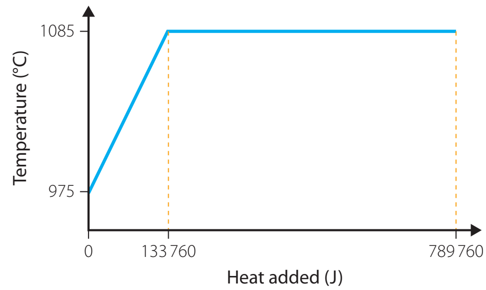
$L_v = 1379.4\,\text{kJ kg}^{-1}$

Calculate the answer

$L_v = 1400\,\text{kJ kg}^{-1}$

Give the answer to the correct number of significant figures

5



6 $Q_{total} = Q_{gas} + -Q_{fusion}$

The total heat released is equal to the sum of the heat released during both phases

$Q_{total} = mc_{gas}\Delta T + -mL_f$

Apply the specific heat and latent heat of fusion formulas

$$Q_{total} = 2.5\,\text{kg} \times 0.248\,\text{kcal kg}^{-1}\,°\text{C}^{-1} \times \left(\frac{4.2\,\text{kJ}}{\text{kcal}}\right) \times (-210°\text{C} - 25°\text{C}) - 2.5\,\text{kg} \times 199\,\text{kJ kg}^{-1}$$

Insert known values in correct SI format

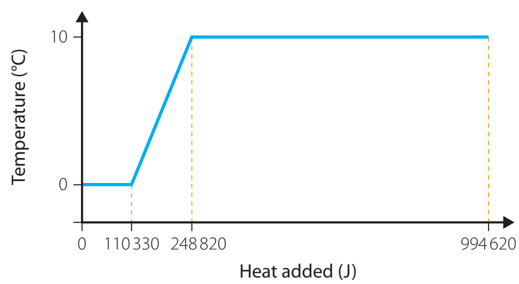
$Q_{total} = -1109.44\,\text{kJ}$

Calculate the answer

$Q_{total} = -1100\,\text{kJ}$

Give the answer to the correct number of significant figures

7 a



b $Q_{total} = Q_{fusion} + Q_{water} + Q_{vaporisation}$

The total heat added is equal to the sum of the heat added during all three stages

$Q_{total} = mL_f + mc_{water}\Delta T + mL_v$

Apply the specific heat and latent heat formulas

$$Q_{total} = (0.33\,kg \times 334\,kJ\,kg^{-1}) + (0.33 \times 4.2\,kJ\,kg^{-1}\,°C^{-1} \times 100°C) + (0.33\,kg \times 2260\,kJ\,kg^{-1})$$

Insert known values

$Q_{total} = 994.620\,kJ$

Calculate the answer

$Q_{total} = 990\,kJ$

Give the answer to the correct number of significant figures

CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 a A change in physical state (e.g. solid to liquid).

b The phase change from solid to liquid.

c The phase change from liquid to solid.

d The phase change from liquid to gas.

e The phase change from gas to liquid.

f The phase change from solid to gas without becoming a liquid.

g The phase change from gas to solid without becoming a liquid.

h The process in which some of the particles with high kinetic energy escape the surface of a liquid at a temperature below its boiling point.

i The heat required to change the state of a substance at its boiling point or melting point without a change in temperature; unit: $J\,kg^{-1}$.

j The heat required to change the state of 1 kg of a substance from a solid to a liquid without a change in temperature.

k The heat required to change the state of 1 kg of a substance from a liquid to a gas without a change in temperature.

2 The temperature of a substance undergoing a phase change remains constant

CATEGORY QUESTIONS

3 Vaporisation is the phase change from liquid to gas at the boiling point, whereas evaporation is the spontaneous escape of high energy liquid particles to the gaseous state below the boiling point.

4 At the melting point, any heat added to a solid becomes stored in the intermolecular bonds as they stretch or compress away from their mean bond length. After all of the particles gain enough energy to overcome their solid state intermolecular bonds, the particles are free to slide past one another and any further heat that is added goes into increasing the kinetic energy of the particles.

ELABORATION QUESTIONS

5 When a substance undergoes evaporation, the particles with the highest amount of kinetic energy escape the substance into the gas phase. Because the substance is losing its most energetic particles, the average kinetic energy of the particles in the substance, and therefore the temperature of the substance, will decrease.

6 During a phase change, all of the heat added is stored as potential energy in the intermolecular bonds of the particles and therefore there is no net increase in the average kinetic energy of the particles. Since temperature is dependent upon the average kinetic energy, there is no increase in temperature.

EVIDENCE QUESTIONS

7 Given enough time, evaporative cooling would result in a significant decrease in the temperature of a substance. The human body, as well as many other organisms, use this in order to reduce their internal temperature through the process of sweating. Scientists use this process to cool objects down to close to absolute zero when conductive cooling is no longer possible.

8 Quite often ice and water will co-exist at the same time indicating that they are at the same temperature. This can be seen in many iced drinks as well as in many bodies of water. The two phases can only be at the same temperature at the phase-change temperature.

END-OF-CHAPTER EXAM

1 D

2 C

3 A

4 C

5 Deposition

6 The process in which some of the particles with high kinetic energy escape the surface of a liquid at a temperature below its boiling point.

7 The heat required to change the state of a substance at its boiling point or melting point without a change in temperature.

8 $Q = mL_v$

Apply latent heat of vaporisation formula

$Q = 3.5\,kg \times 2260\,kJ\,kg^{-1}$

Insert known values

$Q = 7910\,kJ$

Calculate answer

$Q = 7900\,kJ$

Give answer to correct number of significant figures

9 $Q = mL_v$

Apply latent heat of vaporisation formula

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$$m = \frac{Q}{L_v}$$
Rearrange equation to make the mass the subject
$$m = \frac{135\,\text{kJ}}{205\,\text{kJ kg}^{-1}}$$
Insert known values
$$m = 0.658\,54\,\text{kg}$$
Calculate the answer
$$m = 0.659\,\text{kg}$$
Give answer to correct number of significant figures

10 When heat is removed from a substance in the liquid phase, the average kinetic energy of the substance and therefore the temperature decreases, with the continuing collisions ensuring that all particles lose kinetic energy. At the freezing point, the potential energy that is stored in the particles due to their being stretched or compressed away from their mean solid phase intermolecular bond distance is released, resulting in heat being released from the substance.

11 The moist air rises because it is less dense than the dry air. As it ascends into a cooler region of air, the water vapour condenses into a liquid in the form of clouds, releasing its latent heat of vaporisation into the surrounding air, which in turn warms up, becomes less dense and continuing to rise.

12 $Q_{total} = Q_{liquid} + Q_{vaporisation}$

The total heat added is equal to the sum of the heat added for both stages
$$Q_{total} = mc_{liquid}\Delta T + mL_v$$
Apply the specific heat capacity and specific latent heat of vaporisation formulas
$$Q_{total} = 0.5\,\text{kg} \times 2.72\,\text{kJ kg}^{-1}\,°\text{C}^{-1} \times (78°\text{C} - 25°\text{C}) + 0.5\,\text{kg} \times 841\,\text{kJ kg}^{-1}$$
Insert known values
$$Q_{total} = 492.69\,\text{kJ}$$
Calculate the answer
$$Q_{total} = 490\,\text{kJ}$$
Give the answer to the correct number of significant figures

13 $Q_{total} = Q_{ice} + Q_{fusion} + Q_{liquid}$

The total heat added is equal to the sum of the heat added for both stages
$$Q_{total} = mc_{ice}\Delta T + mL_f + mc_{liquid}\Delta T$$
Apply the specific heat capacity and specific latent heat of fusion formulas
$$Q_{total} = m\left(c_{ice}\Delta T + L_f + c_{liquid}\Delta T\right)$$
Factorise the common mass
$$m = \frac{Q_{total}}{c_{ice}\Delta T + L_f + c_{liquid}\Delta T}$$
Make mass the subject
$$m = \frac{380\,\text{kJ}}{2.1\,\text{kJ kg}^{-1}\,°\text{C}^{-1} \times (0°\text{C} - -12°\text{C}) + 334\,\text{kJ} + 4.2\,\text{kJ kg}^{-1}\,°\text{C}^{-1} \times (56°\text{C} - 0°\text{C})}$$
Insert known values
$$m = 0.639\,3\,\text{kg}$$
Calculate the answer
$$m = 0.64\,\text{kg}$$
Give the answer to the correct number of significant figures

14 $P = \frac{Q_{total}}{t}$ (1)

Apply the power formula and call this equation (1)
$$Q_{total} = Q_{added} + Q_{lost}$$
The total heat supplied is equal to the sum of the heat added to the substance and the heat lost
$$Q_{total} = Q_{added} + 0.15 \times Q_{lost}$$
The heat lost is equal to 15% of the heat generated by the hot plate
$$0.85 \times Q_{total} = Q_{added}$$
Gather like terms
$$Q_{total} = \frac{Q_{added}}{0.85} \quad (2)$$
Divide both sides by 0.85 and call this equation (2)
$$Q_{added} = Q_{fusion} + Q_{water} + Q_{vaporisation}$$
The total heat added by the hot plate is equal to the sum of the heat added during all three stages
$$Q_{added} = mL_f + mc_{water}\Delta T + mL_v$$
Apply the specific heat capacity and latent heat formulas
$$Q_{added} = \left(1.6\,\text{kg} \times 334\,000\,\text{J kg}^{-1}\right) + \left(1.6\,\text{kg} \times 4200\,\text{J kg}^{-1}\,°\text{C}^{-1} \times 100°\text{C}\right) + 1.6\,\text{kg} \times 2\,260\,000\,\text{J kg}^{-1}$$
Insert known values
$$Q_{added} = 4\,822\,400\,\text{J} \quad (3)$$
Calculated the heat added to the substance and call this equation (3)
$$Q_{total} = \frac{4\,822\,400\,\text{J}}{0.85}$$
Substitute equation (3) into equation (2)
$$Q_{total} = 5\,673\,411.765\,\text{J} \quad (4)$$
Calculate the total heat generated by the hotplate and call this equation (4)
$$P = \frac{5\,673\,411.765\,\text{J}}{t}$$
Substitute equation (4) into equation (1)
$$P = \frac{5\,673\,411.765\,\text{J}}{10\,\text{min} \times \frac{60\,\text{s}}{1\,\text{min}}}$$
Insert time in SI base units
$$P = 9455.686\,275\,\text{W}$$
Calculate the answer
$$P = 9500\,\text{W}$$
Give the answer to the correct number of significant figures

4.1 SECTION REVIEW

REMEMBERING

1 Two objects in thermal equilibrium have the same temperature

2 The particles of two object in thermal equilibrium have an equal average kinetic energy

UNDERSTANDING

3 Heat flows out of the warmer liquid water into the colder air in the freezer compartment until the two are at thermal equilibrium. This will involve a phase change of the water to ice.

4 Heat flows from the warmer air in the room into the solid ice until the two are at thermal equilibrium. This will involve a phase change of the ice to liquid water.

4.2 SECTION REVIEW

UNDERSTANDING

1 The particles of two objects at thermal equilibrium have the same average kinetic energy, so it is just as likely that collisions between the two will transfer heat in one direction as it is that collisions will transfer heat in the other direction. Therefore, the flow in both directions is equal and the net heat flow is equal to zero, meaning that neither substance will increase or decrease in temperature and they will maintain thermal equilibrium.

2 The particles on the surface of the liquid collide with the cool air in the freezer compartment and transfer some of their kinetic energy to them. These air particles then go on to transfer this higher kinetic energy to other air particles through collisions and the particles in the liquid, which have lost kinetic energy, will gain more kinetic energy through collisions with other particles in the liquid. In this way the average kinetic energy of the air is increased and the average kinetic energy of the water is decreased. This will continue until the freezing point of the liquid, at which point the potential energy stored in the intermolecular bonds will be transferred through collisions to the air particles. After the phase change, the kinetic energy of the surface particles in the newly formed ice will be transferred to the air particles.

3 The particles of air that collide with the surface particles of the liquid will transfer some of their kinetic energy to them. These ice particles then go on to transfer this higher kinetic energy to other ice particles through collisions while the particles in the air, which have lost kinetic energy, will gain more kinetic energy through collisions with other particles in the air. In this way, the average kinetic energy of the ice is increased and the average kinetic energy of the air is decreased. This will continue until the melting point of the ice at which point the kinetic energy imparted by the air particles will be stored as potential energy in the intermolecular bonds. After the phase change, the kinetic energy of the air particles will be transferred to the newly formed water particles until the average kinetic energy of the air particles is equal to the average kinetic energy of the water particles.

4 The particles on the stove element will transfer their high average kinetic energy through the process of conduction to the particles of the saucepan that are in contact with them. The particles in the stovetop, which have lost kinetic energy, will gain more kinetic energy by colliding with other particles in the stovetop. The particles in the saucepan, which have gained kinetic energy, will collide with other particles in the saucepan and transfer heat throughout. This process will continue until the particles in the saucepan which are in contact with the water will have a higher average kinetic energy than the water particles in contact with them and a net heat flow will pass from the saucepan into the water due to this difference. This process will continue until the particles of the stovetop, the saucepan and the water all have the same average kinetic energy and are therefore at thermal equilibrium.

5 Since temperature is defined as the average kinetic energy of a substance, if all three objects are at thermal equilibrium with each other, they must have equal average kinetic energies.

4.3 SECTION REVIEW

REMEMBERING

1 A calorimeter is a device that is highly insulated and is designed to prevent heat loss from the internal cavity to the surroundings. It consists of an internal cavity surrounded by aluminium walls and an insulating material and/or a vacuum between the internal and the external aluminium walls. The internal cavity is said to be thermodynamically isolated,

2 The conservation of energy states that energy can never be created or destroyed, and the equation $Q_{lost} = -Q_{gained}$ simply states that the heat lost by one object is equal in magnitude to the heat gained by another.

UNDERSTANDING

3 a Both energy and mass can be transferred from the system to the surroundings

b Energy but not mass can be transferred from the system to its surroundings

c Neither energy or mass can be transferred from the system to its surroundings

4 a Isolated

b Closed

c Open

d Open

e Isolated

f Closed

APPLYING

5 $Q_{lost} = -Q_{gained}$

Apply the conservation of energy formula

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$m_{hot} c\Delta T_{hot} = -m_{cold} c\Delta T_{cold}$

Apply the specific heat capacity formula

$m_{hot} \Delta T_{hot} = -m_{cold} \Delta T_{cold}$

Cancel c, the specific heat capacity of water from both sides

$m_{hot}\left(T_f - T_{i,hot}\right) = -m_{cold}\left(T_f - T_{i,cold}\right)$

Expand ΔT

$m_{hot} T_f + m_{cold} T_f = m_{hot} T_{i,hot} + m_{cold} T_{i,cold}$

Gather like terms

$\left(m_{hot} + m_{cold}\right) T_f = m_{hot} T_{i,hot} + m_{cold} T_{i,cold}$

Factorise the common T_f from the expression on the left-hand side

$$T_f = \frac{m_{hot} T_{i,hot} + m_{cold} T_{i,cold}}{\left(m_{hot} + m_{cold}\right)}$$

Isolate T_f on the left-hand side of the equation

$$T_f = \frac{2\,kg \times 65°C + 1\,kg \times 10°C}{2\,kg \times 1\,kg}$$

Insert known values recalling that 1 L of water = 1 kg

$T_f = 46.66666667°C$

Calculate the answer

$T_f = 47°C$

Give the answer to the correct number of significant figures

6 $Q_{lost} = -Q_{gained}$

Apply the conservation of energy formula

$m_{hot} c\Delta T_{hot} = -m_{cold} c\Delta T_{cold}$

Apply the specific heat capacity formula

$m_{hot} \Delta T_{hot} = -m_{cold} \Delta T_{cold}$

Cancel c, the specific heat capacity of water from both sides

$m_{hot} T_f - m_{hot} T_{i,hot} = -m_{cold}\left(T_f - T_{i,cold}\right)$

Expand the brackets

$m_{hot} T_{i,hot} = m_{hot} T_f + m_{cold}\left(T_f - T_{i,cold}\right)$

Isolate the term containing the required $T_{i,hot}$ on the left-hand side

$$T_{i,hot} = \frac{m_{hot} T_f + m_{cold}\left(T_f - T_{i,cold}\right)}{m_{hot}}$$

Isolate $T_{i,hot}$ on the left-hand side

$$T_{i,hot} = \frac{2\,kg \times 26°C + 3\,kg \times (26°C - 23°C)}{2\,kg}$$

Insert known values, recalling that 1 L of water = 1 kg

$T_{i,hot} = 30.5°C$

Calculate the answer

$T_{i,hot} = 31°C$

Give the answer to the correct number of significant figures

7 $Q_{lost} = -Q_{gained}$

Apply the conservation of energy formula assuming it is an isolated system due to the blanket

$m_{tea} c_{tea} \Delta T_{tea} = -m_{body} c_{body} \Delta T_{body}$

Apply the specific heat capacity formula

$m_{tea} c_{tea}\left(T_f - T_{i,tea}\right) = -m_{body} c_{body}\left(T_f - T_{i,body}\right)$

Expand the ΔT

$m_{tea} c_{tea} T_f - m_{tea} c_{tea} T_{i,tea} = -m_{body} c_{body} T_f + m_{body} c_{body} T_{i,body}$

Expand the brackets

$m_{tea} c_{tea} T_f + m_{body} c_{body} T_f = m_{tea} c_{tea} T_{i,tea} + m_{body} c_{body} T_{i,body}$

Gather terms containing T_f on the left-hand side

$\left(m_{tea} c_{tea} + m_{body} c_{body}\right) T_f = m_{tea} c_{tea} T_{i,tea} + m_{body} c_{body} T_{i,body}$

Factorise T_f on the left-hand side

$$T_f = \frac{m_{tea} c_{tea} T_{i,tea} + m_{body} c_{body} T_{i,body}}{\left(m_{tea} c_{tea} + m_{body} c_{body}\right)}$$

Isolate T_f on the left-hand side

$$T_f = \frac{0.62\,kg \times 4200\,J\,kg^{-1}\,°C^{-1} \times 60°C + 60\,kg \times 3500\,J\,kg^{-1}\,°C^{-1} \times 33.5°C}{\left(0.62\,kg \times 4200\,J\,kg^{-1}\,°C^{-1} + 60\,kg \times 3500\,J\,kg^{-1}\,°C^{-1}\right)}$$

Insert known values assuming the tea has a specific heat capacity equal to water

$T_f = 33.824575°C$

Calculate the final temperature

$\Delta T_{body} = T_f - T_{i,body}$

The question asks for the *change* in temperature

$\Delta T_{body} = 33.824575°C - 33.5°C$

Insert initial and final temperatures

$\Delta T_{body} = 0.324575°C$

Calculate the answer

$\Delta T_{body} = 0.3°C$

Give the answer to the correct number of significant figures

8 $-Q_{lost} = Q_{gained}$

Apply the conservation of energy formula since it is in a calorimeter

$-m_{sample} c_{sample} \Delta T_{sample} = m_{cal} c_{cal} \Delta T_{cal} + m_{water} c_{water} \Delta T_{water}$

Apply the specific heat capacity formula

$$c_{sample} = \frac{m_{cal} c_{cal} \Delta T_{cal} + m_{water} c_{water} \Delta T_{water}}{-m_{sample} \Delta T_{sample}}$$

Isolate the required c_{sample} on the left-hand side

$$c_{sample} = \frac{0.15\,kg \times 900\,J\,kg^{-1}\,°C^{-1}(38°C - 10°C) + 0.25\,kg \times 4200\,J\,kg^{-1}\,°C^{-1}(38°C - 10°C)}{-1.23\,kg \times (38°C - 98°C)}$$

Insert known values, assuming that the calorimeter is made of aluminium

$c_{sample} = 449.5935\,J\,kg^{-1}\,°C^{-1}$

Calculate the answer

$c_{sample} = 450\,J\,kg^{-1}\,°C^{-1}$

Give the answer to the correct number of significant figures

From Table 2.6.1, the specific heat capacity of the sample is similar to that of iron.

9 $-Q_{lost} = Q_{gained}$

Apply the conservation of energy formula, assuming it is an isolated system

$-m_{iron} c_{iron} \Delta T_{iron} = m_{water} c_{water} \Delta T_{water} + m_{water} L_{v,water}$

Apply the specific heat capacity and latent heat of fusion formulas

$$\Delta T_{\text{iron}} = \frac{m_{\text{water}} c_{\text{water}} \Delta T_{\text{water}} + m_{\text{water}} L_{\text{v,water}}}{-m_{\text{iron}} c_{\text{iron}}}$$

Isolate the ΔT_{iron} on the left-hand side

$$\Delta T_{\text{f,iron}} = \frac{m_{\text{water}} c_{\text{water}} \Delta T_{\text{water}} + m_{\text{water}} L_{\text{v,water}}}{-m_{\text{iron}} c_{\text{iron}}} + T_{\text{i,iron}}$$

Isolate the required $T_{\text{f,iron}}$ on the left-hand side

$$\Delta T_{\text{f,iron}} = \frac{0.1\,\text{kg} \times 4200\,\text{J kg}^{-1}\,°\text{C}^{-1} \times (100°\text{C} - 65°\text{C}) + 0.1\,\text{kg} \times 2\,260\,000\,\text{J kg}^{-1}}{-5\,\text{kg} \times 450\,\text{J kg}^{-1}\,°\text{C}^{-1}}$$

$$+140°\text{C}$$

$$\Delta T_{\text{f,iron}} = 33.022\,26°\text{C}$$

Calculate the answer

$$\Delta T_{\text{f,iron}} = 33°\text{C}$$

Give the answer to the correct number of significant figures

10 $-Q_{\text{lost}} = Q_{\text{gained}}$

Apply the conservation of energy formula, assuming it is an isolated system

$$-m_{\text{steam}} L_{\text{v}} + m_{\text{steam}} c_{\text{water}} \Delta T_{\text{hot}} = -(m_{\text{ice}} L_{\text{f}} + m_{\text{ice}} c_{\text{water}} \Delta T_{\text{cold}})$$

Apply the specific heat capacity and latent heat formulas

$$m_{\text{steam}}(-L_{\text{v}} + c_{\text{water}} \Delta T_{\text{hot}}) = -(m_{\text{ice}} L_{\text{f}} + m_{\text{ice}} c_{\text{water}} \Delta T_{\text{cold}})$$

Factorise the required m_{steam} on the left-hand side

$$m_{\text{steam}} = \frac{-(m_{\text{ice}} L_{\text{f}} + m_{\text{ice}} c_{\text{water}} \Delta T_{\text{cold}})}{(-L_{\text{v}} + c_{\text{water}} \Delta T_{\text{hot}})}$$

Isolate the m_{steam} on the left-hand side

$$m_{\text{steam}} = \frac{-(1\,\text{kg} \times 334\,000\,\text{J kg}^{-1} + 1\,\text{kg} \times 4200\,\text{J kg}^{-1}\,°\text{C}^{-1} \times (22°\text{C} - 0°\text{C}))}{(-2\,260\,000\,\text{J kg}^{-1} + 4200\,\text{J kg}^{-1}\,°\text{C}^{-1}(22°\text{C} - 100°\text{C}))}$$

Insert known values

$$m_{\text{steam}} = 0.6349\,\text{kg}$$

Calculate the answer

$$m_{\text{steam}} = 0.6\,\text{kg}$$

Give the answer to the correct number of significant figures

CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 a The condition in which two or more objects in physical contact have the same temperature and average kinetic energy as each other.

b If two systems are in thermal equilibrium with a third system, then they must be in thermal equilibrium with each other.

c The direction of heat flow is always from a hotter object to a colder object.

d A system which can lose mass and energy to its surroundings.

e A system that can lose energy but not mass to its surroundings

f A system that cannot lose mass or energy to its surroundings

2 Two objects at thermal equilibrium transfer equal amounts of heat to each other, meaning that there is no net heat flowing between them.

CATEGORY QUESTIONS

3 Answers will vary, but should all include examples where objects reach the same temperature. For example:

- air conditioning
- heater
- oven
- fridge.

4 The particles of two or more objects at thermal equilibrium have equal average kinetic energies. Even though collisions may still occur between them, the amount of energy transferred one way is equal to the amount transferred the other.

5 Answers will vary, some examples are provided below.

a A saucepan of water

b A saucepan of water with a lid

c Water in a calorimeter

6 The second law of thermodynamics states that the direction of heat flow is always from a hotter object to a colder object, suggesting that in a state of thermal equilibrium there will be no heat flow. This is true if the heat flow being referred to is the net heat flow. However, in thermal equilibrium there is an equal amount of heat flowing in each direction.

ELABORATION QUESTIONS

7 The zeroth law of thermodynamics states that if two objects are in thermal equilibrium with a third object, then they must be in thermal equilibrium with each other. This means that the particles of all three objects have the same average kinetic energy. The internal energy of all three objects may differ, however, because the amount of energy stored as potential energy in the intermolecular bonds may differ and is likely to depend on the chemical composition of the objects.

8 It is not possible to solve thermal equilibrium problems for open and closed systems because they can both transfer energy to their surroundings. This means that thermal energy in the form of heat will continue to flow in or out of the system even if the system itself is in thermal equilibrium.

9 If the universe is an isolated system, exactly the same amount of energy that was present during the Big Bang is still present in the universe now.

10 If the universe is an isolated system and energy always moves from a hotter object to a colder object, eventually all matter in the universe should reach thermal equilibrium and no net heat will flow between anything.

EVIDENCE QUESTIONS

11 If the object outside of the initial closed system is in an isolated system, then logically that isolated system must include the initial closed system. The initial system could then be expanded to include the external object because the zeroth law of thermodynamics states that if all of the objects in the initial system are in thermal equilibrium with the external object, then they must be in thermal equilibrium with each other.

12 Answers will vary depending on research conducted.

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END-OF-CHAPTER EXAM

1 C

2 C

3 A

4 B

5 Heat

6 Kinetic

7 If two systems are in thermal equilibrium with a third system, then they must be in thermal equilibrium with each other.

8 The direction of heat flow is always from a hotter object to a colder object.

9 $Q_{lost} = -Q_{gained}$

Apply the conservation of energy formula

$m_{hot}c\Delta T_{hot} = -m_{cold}c\Delta T_{cold}$

Apply the specific heat capacity formula

$m_{hot}\Delta T_{hot} = -m_{cold}\Delta T_{cold}$

Cancel c, the specific heat capacity of water from both sides

$m_{hot}\left(T_f - T_{i,hot}\right) = -m_{cold}\left(T_f - T_{i,cold}\right)$

Expand ΔT

$m_{hot}T_f + m_{cold}T_f = m_{hot}T_{i,hot} + m_{cold}T_{i,cold}$

Gather like terms

$(m_{hot} + m_{cold})T_f = m_{hot}T_{i,hot} + m_{cold}T_{i,cold}$

Factorise the common T_f from the expression on the left-hand side

$$T_f = \frac{m_{hot}T_{i,hot} + m_{cold}T_{i,cold}}{(m_{hot} + m_{cold})}$$

Isolate T_f on the left-hand side of the equation

$$T_f = \frac{0.25\,\text{kg} \times 45°\text{C} + 0.15\,\text{kg} \times 12°\text{C}}{0.25\,\text{kg} + 0.15\,\text{kg}}$$

Insert known values, recalling that 1 L of water = 1 kg

$T_f = 32.625°\text{C}$

Calculate the answer

$T_f = 33°\text{C}$

Give the answer to the correct number of significant figures

10 $-Q_{lost} = Q_{gained}$

Apply the conservation of energy formula

$-m_{iron}c_{iron}\Delta T_{iron} = m_{water}L_{v,water}$

Apply the specific heat capacity and latent heat of vaporisation formula

$$\Delta T_{iron} = \frac{m_{water}L_{v,water}}{-m_{iron}c_{iron}}$$

Isolate the ΔT_{iron} on the left-hand side

$$T_{f,iron} = \frac{m_{water}L_{v,water}}{-m_{iron}c_{iron}} + T_{i,iron}$$

Isolate the required T_f of the left-hand side

$$T_{f,iron} = \frac{0.2\,\text{kg} \times 334\,000\,\text{J kg}^{-1}}{-3\,\text{kg} \times 450\,\text{J kg}^{-1}\,°\text{C}^{-1}} + 180°\text{C}$$

Insert known values

$T_{f,iron} = 130.5185°\text{C}$

Calculate the answer

$T_{f,iron} = 131°\text{C}$

Give the answer to the correct number of significant figures

11 The first law of thermodynamics is the law of conservation of energy, which is useful when solving problems involving isolated systems because all of the energy can be accounted for. In the case of these systems, all of the heat lost by one part or parts of the system has to be added to the remaining parts of the system.

12 If equal amounts of heat are added to two objects that are at thermal equilibrium, there is no guarantee that they will still be in thermal equilibrium. This is due to the fact that the temperature changes that each object will undergo will vary depending on their relative specific heat capacities.

13 $-Q_{lost} = Q_{gained}$

Apply the conservation of energy formula, assuming it is an isolated system

$-m_{steam}L_v + m_{steam}c_{water}\Delta T_{hot} = -(m_{ice}L_f + m_{ice}c_{water}\Delta T_{cold})$

Apply the specific heat capacity and latent heat formulas

$m_{steam}(-L_v + c_{water}\Delta T_{hot}) = -(m_{ice}L_f + m_{ice}c_{water}\Delta T_{cold})$

Factorise the required m_{steam} on the left-hand side

$$m_{steam} = \frac{-(m_{ice}L_f + m_{ice}c_{water}\Delta T_{cold})}{(-L_v + c_{water}\Delta T_{hot})}$$

Isolate m_{steam} on the left-hand side

$$m_{steam} = \frac{-\left(1\,\text{kg} \times 334\,000\,\text{J kg}^{-1} + 1 \times 4200\,\text{J kg}^{-1}\,°\text{C}^{-1} \times (25°\text{C} - 0°\text{C})\right)}{\left(-2\,260\,000\,\text{J kg}^{-1} + 4200\,\text{J kg}^{-1}\,°\text{C}^{-1}(25°\text{C} - 100°\text{C})\right)}$$

Insert known values

$m_{steam} = 0.170\,485\,\text{kg}$

Calculate the answer

$m_{steam} = 0.17\,\text{kg}$

Give the answer to the correct number of significant figures

14 $-Q_{lost} = Q_{gained}$

Apply the conservation of energy formula since it is in a calorimeter

$-m_{iron}c_{iron}\Delta T_{iron} = m_{cal}c_{cal}\Delta T_{cal} + m_{water}c_{water}\Delta T_{water}$

Apply the specific heat capacity formulas

$$-m_{iron}c_{iron}\left(T_f - T_{i,iron}\right) = m_{cal}c_{cal}\left(T_f - T_{i,cal}\right) + m_{water}c_{water}\left(T_f - T_{i,water}\right)$$

Expand ΔT on both sides

$$m_{cal}c_{cal}T_f + m_{water}c_{water}T_f + m_{iron}c_{iron}T_f = m_{iron}c_{iron}T_{i,iron} + m_{cal}c_{cal}T_{i,cal} + m_{water}c_{water}T_{i,water}$$

Collect like terms

$$(m_{cal}c_{cal} + m_{water}c_{water} + m_{iron}c_{iron})T_f = m_{iron}c_{iron}T_{i,iron} + m_{cal}c_{cal}T_{i,cal} + m_{water}c_{water}T_{i,water}$$

Factorise the T_f on the left-hand side

$$T_f = \frac{m_{iron}c_{iron}T_{i,iron} + m_{cal}c_{cal}T_{i,cal} + m_{water}c_{water}T_{i,water}}{(m_{cal}c_{cal} + m_{water}c_{water} + m_{iron}c_{iron})}$$

Isolate T_f on the left-hand side

$$T_f = \frac{0.15\,\text{kg} \times 450\,\text{J kg}^{-1}\,°\text{C}^{-1} \times 85°\text{C} + 0.11\,\text{kg} \times 900\,\text{J kg}^{-1}\,°\text{C}^{-1} \times 25°\text{C} + 0.25\,\text{kg} \times 4200\,\text{J kg}^{-1}\,°\text{C}^{-1} \times 25°\text{C}}{0.15\,\text{kg} \times 450\,\text{J kg}^{-1}\,°\text{C}^{-1} + 0.11\,\text{kg} \times 900\,\text{J kg}^{-1}\,°\text{C}^{-1} + 0.25\,\text{kg} \times 4200\,\text{J kg}^{-1}\,°\text{C}^{-1}}$$

Insert known values

$T_f = 28.329°\text{C}$

Calculate the answer

$T_f = 28°\text{C}$

Give the answer to the correct number of significant figures

CHAPTER 5: ENERGY IN SYSTEMS—MECHANICAL WORK AND EFFICIENCY

5.1 SECTION REVIEW

REMEMBERING

1 A thermodynamic system can lose energy in the form of heat or work

2 Work is the energy transferred due to the action of a force over a distance.

3 Power is the amount of energy transferred per unit time.

UNDERSTANDING

4 $P = \frac{E_{transferred}}{t}$

Apply the power formula

$P = \frac{W}{t}$

$E_{transferred}$ = work for a thermodynamic system

$P = \frac{F \times d}{t}$

Apply the work formula: $W = F \times d$. Work is equal to a force applied over a distance

$P = \frac{n \times m}{s}$

Put in the units for force, distance and time

It can therefore be seen that power can have the units of N m s^{-1}

5 Heat from the combustion chamber is used to turn water to steam in the boiler. This steam expands onto the pistons, which turn crankshafts to cause the wheels to turn and ultimately do work on the carriages by pulling them.

APPLYING

6 $P = \frac{W}{t}$

Apply the work formula

$P = \frac{3000\,\text{J}}{15\,\text{s}}$

Insert known values

$P = 200\,\text{J s}^{-1}$

Calculate the answer

$P = 2.0 \times 10^2\,\text{W}$

Give the answer to the correct number of significant figures and use the correct unit

7 $P = \frac{W}{t}$

Apply the work formula

$W = P \times t$

Rearrange to make the required W the subject

$W = 5.0 \times 10^3\,\text{W} \times 2.5\,\text{min} \times \frac{60\,\text{s}}{1\,\text{min}}$

Insert known values in the correct SI units

$W = 750\,000\,\text{J}$

Calculate the answer with the correct number of significant figures

8 $P = \frac{W}{t}$

Apply the work formula

$t = \frac{W}{P}$

Rearrange to make the required t the subject

$t = \frac{F \times d}{P}$

Replace W with $F \times d$

$t = \frac{120\,\text{N} \times 225\,\text{m}}{150\,\text{W}}$

Insert known values

$t = 180\,\text{s}$

Calculate the answer with the correct number of significant figures

5.2 SECTION REVIEW

REMEMBERING

1 The work energy principle states that the change in internal energy of a system is equal to the net heat added to it minus the work done by it.

2 A heat engine is a device that turns heat energy into work.

3 The stable operating temperature of a heat engine occurs when the net heat in and the work done are equal.

UNDERSTANDING

4 Positive

5 Negative

6 Negative

7 Positive

APPLYING

8 $\Delta U = Q - W$

Apply the work–energy principle

$\Delta U = 2500\,\text{J} - 1200\,\text{J}$

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Insert known values

$\Delta U = 1300\ \text{J}$

Calculate the answer to the correct number of significant figures

9 $\Delta U = Q - W$

Apply the work–energy principle

$\Delta U = Q_{in} - Q_{out} - W$

Include heat lost in the equation

$\Delta U = 5\ \text{kJ} - 1.5\ \text{kJ} - 3.0\ \text{kJ}$

Insert known values

$\Delta U = 0.50\ \text{kJ}$

Calculate the answer to the correct number of significant figures

10 $\Delta U = Q - W$

Apply the work–energy principle

$\Delta U = Q_{in} - Q_{out} - W$

Include heat lost in the equation

$Q_{out} = Q_{in} - \Delta U - W$

Rearrange for Q_{out}

$Q_{out} = 440\ \text{kJ} - 0 - 323\ \text{kJ}$

Insert known values remembering that $\Delta U = 0$ at the stable operating temperature

$Q_{out} = 117\ \text{kJ}$

Calculate the answer

$Q_{out} = 120\ \text{kJ}$

Give the answer to the correct number of significant figures

5.3 SECTION REVIEW

REMEMBERING

1 Useable energy is the energy that can be utilised to perform some desired result; usually in the form of energy to do work.

2 A heat-exchange system is any system that transfers heat from a warmer to a cooler place.

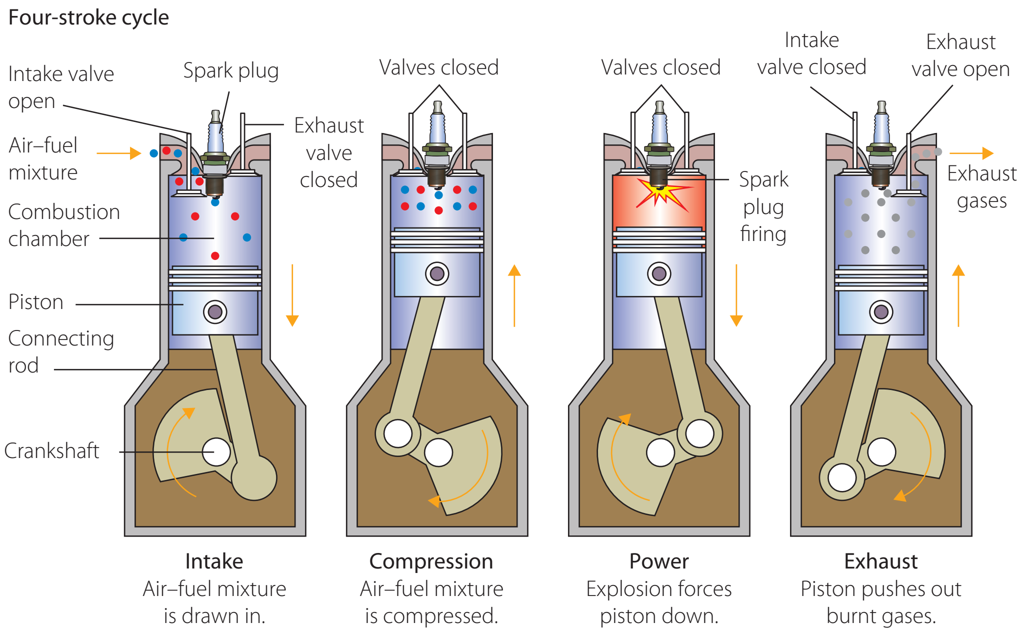
3 A heat-exchange system transfers energy while a heat-conversion system transforms energy.

4 In an internal combustion system the combustion which is used to convert heat energy to work takes place inside of the system, whereas in an external combustion system the combustion takes place outside of the system and the heat is transferred into it.

UNDERSTANDING

5 A refrigerator will not cool the room it is in because the design of the system is that it removes heat from inside the fridge to its surroundings. Therefore, any heat removed from the room if the refrigerator door is left open will immediately be transferred back into the room.

6 See diagram below.



5.4 SECTION REVIEW

REMEMBERING

1 The efficiency of a system is the fraction of input energy that is converted in a thermodynamic process to useful output energy.

APPLYING

2 a $\eta = \frac{\text{energy output}}{\text{energy input}} \times \frac{100\%}{1}$

Apply the efficiency formula

$\eta = \frac{35\,\text{kJ}}{105\,\text{kJ}} \times \frac{100\%}{1}$

Insert known values

$\eta = 33\%$

Calculate the answer with the correct number of significant figures

b The remaining 70 kJ of energy would have been lost as heat to the external environment

3 $\eta = \frac{\text{energy output}}{\text{energy input}} \times \frac{100\%}{1}$

Apply the efficiency formula

$\text{energy output} = \text{energy input} \times \frac{\eta}{100\%}$

Rearrange the equation to make the required energy output the subject

$\text{energy output} = 900\,\text{J} \times \frac{25\%}{100\%}$

Insert known values

$\text{energy output} = 225\,\text{J}$

Calculate the answer

$\text{energy output} = 200\,\text{J}$

Give the answer to the correct number of significant figures

4 $\eta = \frac{W}{Q_{in}} \times \frac{100\%}{1}$

Apply the efficiency formula

$\eta = \frac{350\,\text{kJ}}{1700\,\text{kJ}} \times \frac{100\%}{1}$

Insert known values

$\eta = 20.5882\%$

Calculate the answer

$\eta = 21\%$

Give the answer to the correct number of significant figures

5 a $\eta = \frac{Q_{in} - Q_{out}}{Q_{in}} \times \frac{100\%}{1}$

Apply the efficiency formula

$\frac{\eta}{100\%} \times Q_{in} = Q_{in} - Q_{out}$

Multiply both sides of the equation by $\frac{Q_{in}}{100\%}$

$Q_{in} - \frac{\eta}{100\%} \times Q_{in} = Q_{out}$

Gather the terms containing the required Q_{in} on the left-hand side

$Q_{in}\left(1 - \frac{\eta}{100\%}\right) = Q_{out}$

Factorise Q_{in} out of the left-hand side

$Q_{in} = \frac{Q_{out}}{\left(1 - \frac{\eta}{100\%}\right)}$

Rearrange the equation to make the required Q_{in} the subject

$Q_{in} = \frac{115\,\text{kJ}}{\left(1 - \frac{19\%}{100\%}\right)}$

Insert known values

$Q_{in} = 141.975\,\text{kJ}$

Calculate the answer

$Q_{in} = 140\,\text{kJ}$

Give the answer to the correct number of significant figures

b $\Delta U = Q_{in} - Q_{out} - W$

Apply the work–energy principle

$W = Q_{in} - Q_{out} - \Delta U$

Rearrange the equation to make the required W the subject

$W = 141.975\,\text{kJ} - 115\,\text{kJ} - 0$

Insert known values, remembering that $\Delta U = 0$ at the stable operating temperature

$W = 26.9753\,\text{kJ}$

Calculate the answer

$W = 27\,\text{kJ}$

Give the answer to the correct number of significant figures

CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 a The energy transferred due to the action of a force over a distance

b The transfer of thermal energy

c The sum of the kinetic and potential energies of the particles in a substance

d Energy that can be utilised to perform some desired result; usually in the form of energy to do work

e A system that transfers heat from a warmer to a cooler place

f A system that transforms the internal energy of a system

g A system that moves thermal energy from one place to another

h A system that converts heat energy to work

i A device to produce work through the expansion of a fluid which is heated by the combustion of an external fuel source

j The fraction of input energy that is converted in a thermodynamic process to useful output energy

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CATEGORY QUESTIONS

2 The work energy principle states that the change in internal energy of a system is equal to the net heat added to it minus the work done by it.

3 The internal energy of a system can be increased either by adding heat to it or by doing work on it.

4 The internal energy of a system can be decreased either by removing heat from it or by it doing work.

5 The steam engine converts heat to work by combusting a fuel to create heat, which is then used to turn water to steam. This expanding steam then does work on the pistons of the engine which can transfer this work energy to the required place.

6 Answers may vary but should include any system where heat is transferred from one form to another

ELABORATION QUESTIONS

7 A loss of energy in the form of a movement of heat out of a system or by work being done by a system results in a decrease in the internal energy of the system. For this to occur, the particles of the system must have either lost kinetic energy and therefore cooled down or have lost potential energy and be in the process of a phase change.

8 Answers will vary but should include mention of:

- heat lost to surroundings
- friction
- change in internal energy.

9 Answers will vary but should suggest that the two work together.

10 Answers will vary but may include discussion of:

- increase in energy in environment
- inefficiency
- reduced fuels stocks
- need to create more efficient engines or sustainable sources of energy.

EVIDENCE QUESTIONS

11 Answers will vary but should include examples such as:

- the IT boom
- the search for sustainable energies
- robotics
- transportation.

12 Answers will vary but may include discussion of increased availability of resources and the heat death model of the universe.

END-OF-CHAPTER EXAM

1 C

2 A

3 D

4 B

5 Open

6 Efficiency

7 Power is the amount of energy transferred in a unit of time.

8 The work energy principle states that the change in internal energy of a system is equal to the net heat added to it minus the work done by it.

9 Useable energy is the energy that can be utilised to perform some desired result; usually in the form of energy to do work.

10 $\Delta U = Q - W$

Apply the work–energy principle

$\Delta U = -1800\text{ J} - (-2500\text{ J})$

Insert known values

$\Delta U = 7.0 \times 10^2\text{ J}$

Calculate the answer to the correct number of significant figures

11 $\eta = \frac{W}{Q_{in}} \times \frac{100\%}{1}$

Apply the efficiency formula

$\eta = \frac{1.6\text{ kJ}}{8.5\text{ kJ}} \times \frac{100\%}{1}$

Insert known values

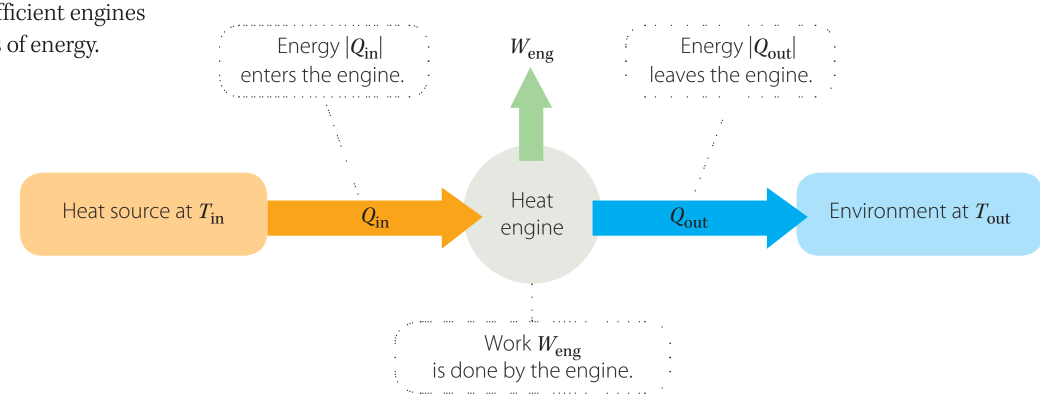
$\eta = 18.8235\%$

Calculate the answer

$\eta = 19\%$

Give the answer to the correct number of significant figures

12 The steam engine converts heat to work by combusting a fuel to create heat, which is then used to turn water to steam. This expanding steam then does work on the pistons of the engine that can transfer this work energy to the required place.



13 $\Delta U = Q - W$

Apply the work–energy principle

$\Delta U = Q_{in} - Q_{out} - W$

Include heat lost in the equation

$W = Q_{in} - Q_{out} - \Delta U$

Rearrange for the required W

$W = 5\,kJ - 1.2\,kJ - 0$

Insert known values, remembering that $\Delta U = 0$ at the stable operating temperature

$W = 3.8\,kJ$

Calculate the answer to the correct number of significant figures

14 a $\eta = \frac{W}{Q_{in}} \times \frac{100\%}{1}$

Apply the efficiency formula

$Q_{in} = \frac{W}{\eta} \times \frac{100\%}{1}$ (1)

Rearrange the equation for the required Q_{in} and call this equation (1)

$P = \frac{W}{t}$

Apply the power formula

$W = P \times t$

Rearrange to make W the subject

$W = 12\,000\,W \times 1\,min \times \frac{60\,s}{1\,min}$

Insert known values in correct SI format

$W = 720\,kJ$

Calculate the amount of work produced in a minute

$Q_{in} = \frac{720\,kJ}{15\%} \times \frac{100\%}{1}$

Insert known values into equation (1)

$Q_{in} = 4800\,kJ$

Calculate the answer to the correct number of significant figures

b $\Delta U = Q - W$

Apply the work–energy principle

$\Delta U = Q_{in} - Q_{out} - W$

Include heat lost in the equation

$Q_{out} = Q_{in} - W - \Delta U$ (1)

Rearrange for the required Q_{out} and call this equation (1)

$Q_{in} = 4800\,kJ \times \frac{1}{60\,s}$

Calculate the amount of heat energy added every second

$Q_{in} = 80\,kJ$

$W = 720\,kJ \times \frac{1}{60\,s}$

Calculate the amount of work produced every second

$W = 12\,kJ$

$Q_{out} = 80\,kJ - 12\,kJ - 0$

Insert known values into equation (1), remembering that $\Delta U = 0$ at the stable operating temperature

$Q_{out} = 68\,kJ$

Calculate the answer to the correct number of significant figures

CHAPTER 6: NUCLEAR MODEL AND STABILITY

6.1 SECTION REVIEW

REMEMBERING

1 Proton (positive), neutron (neutral), electron (negative)

2 Thomson, Rutherford, Bohr

UNDERSTANDING

3 New experiences are constantly providing new evidence of the behaviour of atoms and subatomic particles. From this evidence, we can refine our current understanding of what the atom is like. Evidence continues to be compiled as technology advances, and models of the atom are refined accordingly.

ANALYSING

4 Key differences include the electron configuration and explanation for electron energy levels to explain why electrons don't spiral into the nucleus. Bohr's model accounts for the conservation of energy and momentum while electrons still orbit within given energy states at outer edges of the atom.

6.2 SECTION REVIEW

REMEMBERING

1 A: mass (nucleon) number, Z: atomic (proton) number, X: element symbol

2 Element: a substance that only has atoms with the same number of protons. Isotope: elements with the same number of protons, but a different number of neutrons in the nucleus. Nuclide: elements with the same number of protons and neutrons, and with the nucleus in the same energy state.

UNDERSTANDING

3 Atomic mass is the total number of protons and neutrons in the nucleus – an integer value, where atomic weight is the weighted average of all the masses of the different nuclides of a naturally occurring sample of the element – a non-integer value.

4 No. Electrons do not exist in the nucleus and are used for bonding.

APPLYING

5 $N = A - Z$

$N = 136 - 57$

$N = 79$ neutrons

6 $153 \times 0.5218 + 151 \times 0.4782$

$= 152.04$

ANALYSING

7 If talking about 'the element' hydrogen, it could mean hydrogen-1, hydrogen-2 or hydrogen-3, all of which have different masses. This could cause confusion, as different isotopes have different properties even if they are all the same element.

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8 Molybdenum-98. If a neutron is absorbed by a nucleus, the same number of protons are present, only the mass number changes.

6.3 SECTION REVIEW

REMEMBERING

1 Strong, electrostatic (electromagnetic), weak, gravitational.

2 It is the force responsible for keeping nuclei, and hence atoms, together. And as atoms and matter make up the universe, it can be considered the most important of all forces.

UNDERSTANDING

3 The electrostatic force within nuclei will push protons apart, hence atoms would not stay together. If atoms are unable to stay together, matter would not exist as we know it.

4 $F = \frac{kqQ}{r^2}$

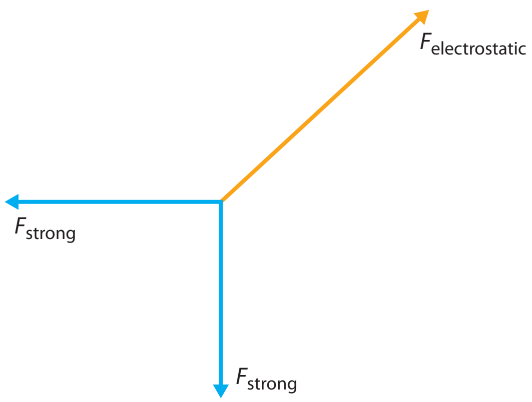
$F = \frac{9 \times 10^9 \times (1.6 \times 10^{-19})^2}{(6 \times 10^{-15})^2}$

$F = \frac{2.304 \times 10^{-28}}{3.6 \times 10^{-29}}$

$F = 6.4$ N of repulsion

ANALYSING

5 Consider the proton in the top right corner. It experiences the following forces:



Notice all forces are balanced so the proton will not move. The gravitational force is so small it is not labelled in this instance, but would point left, down, and towards the other proton.

6 The strong force needs to be exerted on both protons in helium-4 in two directions. Protons exert a repulsive force on each other of 57.6 (from worked example 6.3.1). Then we can calculate the magnitude of the strong force on one proton as follows:

$$F^2_{electrostatic} = F^2_{strong} + F^2_{strong}$$

$$F^2_{electrostatic} = 2 \times F^2_{strong}$$

$$57.6^2 = 2 \times F^2_{strong}$$

$$F^2_{strong} = 1658.88$$

$$F_{strong} = 40.73\text{ N}$$

As the strong force is acting in two directions, on two protons, the total strong force magnitude is $4 \times 40.73 = 162.92$ N.

6.4 SECTION REVIEW

REMEMBERING

1 If a nucleus is stable, it is one of the dots on the line of stability. A stable nucleus has a ratio of protons to neutrons where the interacting forces are balanced.

2 The line of stability, or the stability curve, shows a dot for each isotope of each element which is stable.

UNDERSTANDING

3 No, it would not. This ratio is not on the line of stability, and therefore is considered an unstable nuclide.

CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 As per glossary

2 Protons, neutrons and electrons

CATEGORY QUESTIONS

3 The exchange of mesons between nucleons causes the strong nuclear force, which keeps nuclei and hence atoms together.

4 An isotope is a more specific way to describe an element. An element is defined by the number of protons in the nucleus, an isotope is defined by how many neutrons are in the nucleus of an element.

5 Isotopes are named by their mass number (number of nucleons), as opposed to number of neutrons or protons.

ELABORATION QUESTIONS

6 It is the force responsible for keeping nuclei, and hence atoms, together. And as atoms and matter make up the universe, it can be considered the most important of all forces.

7 Electrons cause the net charge on an atom to change. Electrons do not define an element as they are not in the nucleus of an atom. An element is defined by the components of its nucleus, specifically the number of protons.

8 A stable nucleus has a ratio of protons to neutrons where the interacting forces are balanced. A nucleus becomes unstable when there are too many protons, too many neutrons or too many of both within the nucleus.

EVIDENCE QUESTIONS

9 Answers will vary depending on research conducted.

10 Answers will vary depending on research conducted.

END-OF-CHAPTER EXAM

1 B

2 D

3 C

4 D

5 Rubidium-85

6 Electrostatic force

7 On a very small distance for very small masses, the strong nuclear force. Over very large distances for very large masses, gravitational force.

8 If a nucleus is stable, it is one of the dots on the line of stability. A stable nucleus has a ratio of protons to neutrons where the interacting forces are balanced.

9 A stable nucleus has a ratio of protons to neutrons where the interacting forces are balanced. A nucleus becomes unstable when there are too many protons, too many neutrons or too many of both within the nucleus.

10 Response should include the gold foil experiment, and that electrons must have discrete energy levels so that energy and momentum is conserved.

11 Responses will vary. Protons and neutrons are composed of smaller particles, as there is an exchange between protons and nucleons that provides the strong nuclear force. Electrons are not composed of anything smaller.

CHAPTER 7: SPONTANEOUS DECAY AND HALF-LIFE

7.1 SECTION REVIEW

REMEMBERING

1 Ionising and non-ionising

2 Terrestrial (from Earth's crust) and cosmic (from space)

UNDERSTANDING

3 Ionising radiation and non-ionising radiation are categorised in terms of whether the electron configuration is altered. As the name suggests, ionising radiation can cause electrons to be taken away from atoms, leaving behind ions. It is important to classify these, as different radiations have different uses.

4 Different energy waves help serve different purposes, and also have different effects on biological organisms. It is important to define which energy waves are which for both of these reasons.

APPLYING

5 Background radiation needs to be considered so that when the radioactivity from a source is measured, it is not overestimated. The data needs to be calibrated by deducting the original background radiation from the measurements to have a true indication of what the measured radiation from a source is.

ANALYSING

6 Terrestrial radiation is caused by the decay of nuclei in Earth's crust. As this radiation emanates outwards, it then bounces back in when it hits the atmosphere. Other planets are unable to achieve this due to their lack of atmosphere.

7 Answers will vary but may include: radiographer, types of engineers and nuclear power plant workers.

7.2 SECTION REVIEW

REMEMBERING

1 Mass number and atomic number

2 Alpha decay: ${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha$, beta-minus decay: ${}^{A}_{Z}X \rightarrow {}_{Z+1}^{A}Y + {}_{-1}^{0}\beta + \bar{\nu}$, beta-plus decay: ${}^{A}_{Z}X \rightarrow {}_{Z-1}^{A}Y + {}_{1}^{0}\beta + \nu$, Gamma decay: ${}^{A}_{Z}X_{*} \rightarrow {}^{A}_{Z}X + \gamma$

UNDERSTANDING

3 In nuclear reactions, the nucleus rearranges and new elements are formed. In chemical reactions, bonds will have rearranged but the nuclei of all atoms have the same configuration.

4 Neon-21

APPLYING

5 ${}^{151}_{67}Ho \rightarrow {}^{147}_{65}Tb + {}^{4}_{2}\alpha$, daughter nuclide is terbium-147

6 ${}^{210}_{86}Rn \rightarrow {}^{206}_{84}Po + {}^{4}_{2}\alpha$, an alpha particle is emitted

7 a ${}^{211}_{87}Fr \rightarrow {}^{207}_{85}At + {}^{4}_{2}\alpha$

b Astatine-207

8 a ${}^{213}_{84}Po \rightarrow {}^{209}_{82}Pb + {}^{4}_{2}\alpha$

b Lead-209

ANALYSING

9 ${}^{158}_{65}Tb \rightarrow {}^{154}_{63}Eu_{*} + {}^{4}_{2}\alpha$, ${}^{154}_{63}Eu_{*} \rightarrow {}^{154}_{63}Eu + \gamma$

10 ${}^{198}_{79}Au \rightarrow {}^{198}_{80}Hg + {}^{0}_{-1}\beta$, beta-minus decay.

7.3 SECTION REVIEW

REMEMBERING

1 a Gamma

b Alpha

c All types – depending on the exposure levels

2 Alpha particles and positrons (beta-plus) are both deflected in the same way in magnetic fields.

UNDERSTANDING

3 Gamma radiation, because gamma radiation is a type of electromagnetic radiation with no charge.

4 Alpha radiation; as it is the most massive it is harder to deflect. Its mass/charge ratio is much larger than any other form of radiation.

APPLYING

5 A count rate is how many electric pulses the counter received in a given time period. This is a measurement of how many nuclei are decaying in a radioactive sample.

ANALYSING

6 $\frac{1600}{20} = 80$ counts per second

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7.4 SECTION REVIEW

REMEMBERING

1 An element that can only be produced synthetically, and does not exist naturally in the universe

2 By bombarding nuclei with neutrons.

UNDERSTANDING

3 Arrow on the line of stability will go directly toward the origin, two spaces down and two spaces left as neutron number and proton number decrease by two each. Daughter nuclide is Thorium-234.

4 Vertical arrow upwards by one atomic number increment. Neutron number remains the same. Daughter nuclide is Uranium-233.

ANALYSING

5 Answers will vary depending on research conducted. Positives should include that we can harness transuranic elements for obtaining energy, negatives include their high levels of radiation and instability.

7.5 SECTION REVIEW

REMEMBERING

1 $^{4}_{2}\text{He}, ^{4}_{2}\alpha$

2 $^{0}_{-1}\text{e}, ^{0}_{-1}\beta, ^{0}_{1}\text{e}, ^{0}_{1}\beta$

APPLYING

3 a $^{23}_{12}\text{Mg} \rightarrow ^{23}_{13}\text{Al} + ^{0}_{-1}\beta$, aluminium-23

b $^{81}_{36}\text{Kr} \rightarrow ^{81}_{37}\text{Rb} + ^{0}_{-1}\beta$, rubidium-81

c $^{137}_{55}\text{Cs} \rightarrow ^{137}_{56}\text{Ba} + ^{0}_{-1}\beta$, barium-137

4 a $^{11}_{6}\text{C} \rightarrow ^{11}_{5}\text{B} + ^{0}_{1}\beta$, boron-11

b $^{121}_{53}\text{I} \rightarrow ^{121}_{52}\text{Te} + ^{0}_{1}\beta$, tellurium-121

c $^{15}_{8}\text{O} \rightarrow ^{15}_{7}\text{N} + ^{0}_{1}\beta$, nitrogen-15

5 a $^{233}_{92}\text{U} \rightarrow ^{229}_{90}\text{Th} + ^{4}_{2}\alpha$, thorium-229

b $^{240}_{94}\text{Pu} \rightarrow ^{236}_{92}\text{U} + ^{4}_{2}\alpha$, uranium-236

c $^{222}_{86}\text{Rn} \rightarrow ^{218}_{84}\text{Po} + ^{4}_{2}\alpha$, polonium-218

7.6 SECTION REVIEW

REMEMBERING

1 $N = N_0 e^{-\lambda t}$

2 A measure of the magnitude of radioactive emissions, measured in emissions per second or becquerels (Bq).

APPLYING

3 $N = N_0 e^{-\lambda t}$

$N = 1 \times e^{-2\times10^{-6}\times260}$

$N = 0.9995\,\text{kg}$

4 $N = N_0 e^{-\lambda t}$

$N_0 = N \times e^{\lambda t}$

$N_0 = 300 \times e^{7.9\times10^{-3}\times27}$

$N_0 = 371.33\,\text{g}$

5 $N = N_0 e^{-\lambda t}$

$\frac{N}{N_0} = e^{-\lambda t}$

$0.58 = e^{-\lambda\times1257}$

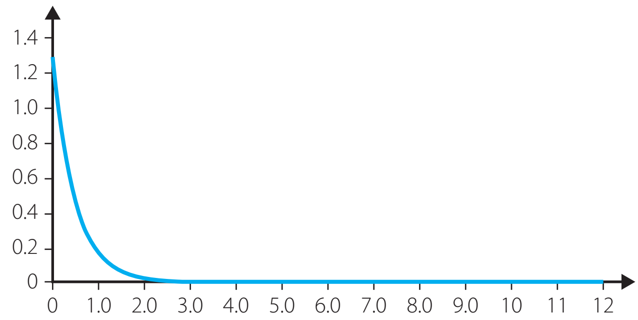
$\ln 0.58 = -\lambda \times 1257$

$\lambda = \frac{0.5447}{1257}$

$\lambda = 4.33 \times 10^{-4}\ \text{yr}^{-1}$

ANALYSING

6 Plot of equation $y = 1.3 \times 10^{26} \times e^{-2t}$ for domain $0 \le t \le 12$



7.7 SECTION REVIEW

REMEMBERING

1 Radium, actinium, thorium, neptunium

2 82 for radium, actinium and thorium. 81 for neptunium.

3 Neptunium series

UNDERSTANDING

4 This is the atomic number where neutron/proton ratios begin to stabilise.

APPLYING

5 $^{238}_{92}\text{U} \rightarrow ^{234}_{90}\text{Th} + ^{4}_{2}\alpha$

$^{234}_{90}\text{Th} \rightarrow ^{234}_{91}\text{Pa} + ^{0}_{-1}\beta$

$^{234}_{91}\text{Pa} \rightarrow ^{234}_{92}\text{U} + ^{0}_{-1}\beta$

$^{234}_{92}\text{U} \rightarrow ^{230}_{90}\text{Th} + ^{4}_{2}\alpha$

$^{230}_{90}\text{Th} \rightarrow ^{226}_{88}\text{Ra} + ^{4}_{2}\alpha$

$^{226}_{88}\text{Ra} \rightarrow ^{222}_{86}\text{Rn} + ^{4}_{2}\alpha$

$^{222}_{86}\text{Rn} \rightarrow ^{218}_{84}\text{Po} + ^{4}_{2}\alpha$

$^{218}_{84}\text{Po} \rightarrow ^{214}_{82}\text{Pb} + ^{4}_{2}\alpha$

$^{214}_{82}\text{Pb} \rightarrow ^{214}_{83}\text{Bi} + ^{0}_{-1}\beta$

$^{214}_{83}\text{Bi} \rightarrow ^{214}_{84}\text{Po} + ^{0}_{-1}\beta$

$^{214}_{84}\text{Po} \rightarrow ^{210}_{82}\text{Pb} + ^{4}_{2}\alpha$

$^{210}_{82}\text{Pb} \rightarrow ^{210}_{83}\text{Bi} + ^{0}_{-1}\beta$

$^{210}_{83}\text{Bi} \rightarrow ^{210}_{84}\text{Po} + ^{0}_{-1}\beta$

$^{210}_{84}\text{Po} \rightarrow ^{206}_{82}\text{Pb} + ^{4}_{2}\alpha$

6 a $^{232}_{90}\text{Th} \rightarrow {}^{228}_{88}\text{Ra} + {}^{4}_{2}\alpha$

$^{228}_{88}\text{Ra} \rightarrow {}^{228}_{89}\text{Ac} + {}^{0}_{-1}\beta$

b Radium-228 and Actinium-228

7 a $^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\alpha$

$^{234}_{90}\text{Th} \rightarrow {}^{234}_{91}\text{Pa} + {}^{0}_{-1}\beta$

b Thorium-234 and Protactinium-234

7.8 SECTION REVIEW

REMEMBERING

1 The time it takes for half of a radioactive substance to decay.

2 $N = N_0\left(\frac{1}{2}\right)^n$

UNDERSTANDING

3 Three decays would have been expected in 9 minutes, but decay is spontaneous, and there is a 50% chance at any point a nucleus will decay. The chance of a nucleus decaying in the first four half-lives (12 minutes) is 1 in 2^4 or 6.25%.

APPLYING

4 $\lambda = \frac{\ln 2}{t_{\frac{1}{2}}}$

$\lambda = \frac{\ln 2}{5730}$

$\lambda = 1.21 \times 10^{-4}\ \text{yr}^{-1}$

5 a $N = N_0\left(\frac{1}{2}\right)^n$

$N = 3 \times 10^{24}\left(\frac{1}{2}\right)$

$N = 1.5 \times 10^{24}$ atoms

b 1.5×10^{24} atoms

6 $N = N_0\left(\frac{1}{2}\right)^n$

$\frac{N}{N_0} = \left(\frac{1}{2}\right)^n$

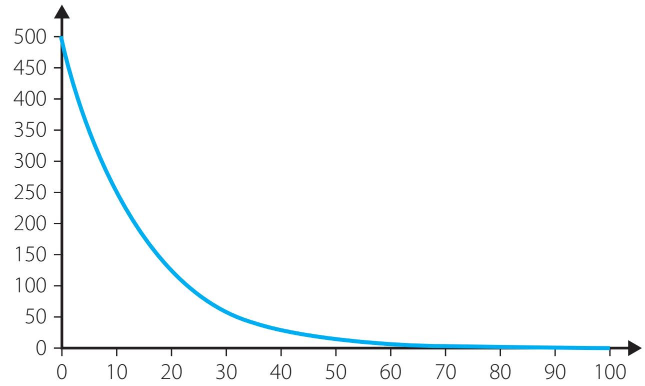
$0.3 = \left(\frac{1}{2}\right)^n$

$\log_{\frac{1}{2}} 0.3 = n$

$n = 1.74$ half-lives

ANALYSING

7 Plot function $y = 500 \times e^{-0.0693t}$ for domain $0 \le t \le 100$



7.9 SECTION REVIEW

REMEMBERING

1 Nuclear medicine, including PET scans. Radioactive dating to determine the age of fossils.

UNDERSTANDING

2 A diagnosis is when the problem is determined. A treatment works to fix the problem.

3 The half-life needs to be considered for the transportation of the isotope so that it can still be administered to the patient with enough nuclei still ready to decay.

APPLYING

4 To ensure not too many of the nuclei decay during creation and transportation so it can be administered and used effectively.

5 Carbon-14 decays after a biological organism dies. The ratio of carbon-14 to carbon-12 can be used to find how many half-lives of carbon-14 have passed since the organism died.

ANALYSING

6 No. The half-life of carbon-14 is much too long to be useful for testing the age of carbon-based life forms that are only hundreds of years old.

CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 Refer to glossary

2 Alpha, beta and gamma

CATEGORY QUESTIONS

3 In order from strongest to weakest ionising power: alpha, beta, gamma radiation.

4 All radioactive decay is spontaneous. There is no way to predict when a single nuclide would decay. The best way it can be approximated is if a large enough sample is obtained a half-life can be experimentally determined.

5 Diagnosis, treatment, dating of fossils, finding leaks in pipes. Students may have different examples.

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ELABORATION QUESTIONS

6 Too many protons will cause a repulsive force too large in the nucleus, so the strong force must be increased. Neutrons help provide the strong force. A proton can *convert* into a neutron by emitting an electron, causing the nucleus to become more stable.

7 To determine whether the exposure over time will be harmful or not.

8 Gamma radiation does not have a charge. Only charged particles are deflected in electric and magnetic fields.

EVIDENCE QUESTIONS

9 Answers will vary but should include ratio of C-14 to C-12 in fossils.

10 Answers will vary. Some sources on Earth include: uranium in Earth's crust, plants and cosmic radiation. On Mars, cosmic radiation is still present.

END-OF-CHAPTER EXAM

1 C

2 A

3 A

4 B

5 D

6 Alpha particle

7 $^{60}_{27}\text{Co} \rightarrow ^{60}_{28}\text{Ni} + ^{0}_{-1}\beta$, the daughter nuclide is nickel-60

8 Beta-minus

9 Gamma, beta, alpha

10 Mass number and atomic number

11 $^{218}_{84}\text{Po} \rightarrow ^{214}_{82}\text{Pb} + ^{4}_{2}\alpha$

$^{214}_{82}\text{Pb} \rightarrow ^{214}_{83}\text{Bi} + ^{0}_{-1}\beta$

12 $\frac{90}{400} = \left(\frac{1}{2}\right)^n$

$n = \log_{\frac{1}{2}}\left(\frac{90}{400}\right)$

$n = 2.15$

2.15 half-lives have elapsed in 18 minutes.

Therefore, the half-life is $\frac{18}{2.15} = 8.36$ minutes.

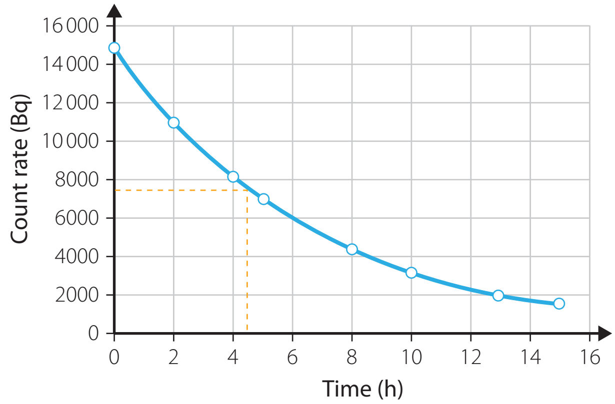
13 $\lambda = \frac{\ln 2}{t_{\frac{1}{2}}}$

$\lambda = \frac{\ln 2}{1700}$

$\lambda = 4.1 \times 10^{-4}$ Bq

14 An unstable nuclide can become stable through a series of alpha and beta decays depending on what components in the nucleus are causing the instability. If a nucleus has too many protons, it will undergo beta-plus decay; if it has too many neutrons, it will undergo beta-minus decay, and if it has too many nucleons, it will undergo alpha decay.

15 a Plot the function, draw a trend line, and interpolate to when the count rate is 7500 Bq.



b Half-life = 4.5 hours

16 Answers will vary, but discussion of the $\frac{N}{N_0}$ ratio should be included in response.

CHAPTER 8 NUCLEAR ENERGY AND MASS DEFECT

8.1 SECTION REVIEW

REMEMBERING

1 E: Energy, the energy released in a nuclear reaction, measured in joules.

Δm: Mass defect, the difference between the mass of an atom and that of its constituent parts, measured in kilograms.

c: The speed of light, $c = 3.00 \times 10^8\ \text{m s}^{-1}$

2 a Electromagnetic force: the force of attraction or repulsion that acts between charged particles.

b Strong nuclear force: the force acting to bind nucleons together.

c Gravitational force: the force of attraction acting at a distance between masses.

d Weak nuclear force: the force acting between subatomic particles within the nucleus; responsible for beta decay.

e Nuclear binding energy: the energy required to disassemble a nucleus into its component nucleons.

UNDERSTANDING

3

	GRAVITATIONAL FORCE	WEAK NUCLEAR FORCE	ELECTROMAGNETIC FORCE	STRONG NUCLEAR FORCE
Relative magnitude	1	10^{32}	10^{36}	10^{40}
Range (m)	Indefinite	10^{-18} or 1 attometre, 1 am	Infinite	10^{-15} or 1 femtometre, 1 fm

APPLYING

4 a $\Delta m = 1.376 \times 10^{-29}$ kg

b $E = 1.238 \times 10^{-12}$ J

c $E = 4.128 \times 10^{-13}$ J per nucleon

5 a $\Delta m = 1.760\,45 \times 10^{-28}$ kg

b $E = 1.584\,41 \times 10^{-11}$ J

c $E = 1.1317 \times 10^{-12}$ J per nucleon

8.2 SECTION REVIEW

REMEMBERING

1 a Natural transmutation

b Artificial transmutation

APPLYING

2 ${}^{14}_{7}\text{N} + {}^{4}_{2}\text{He} \rightarrow {}^{18}_{9}\text{F}$

8.3 SECTION REVIEW

REMEMBERING

1 ${}^{238}_{92}\text{U}$

2 Fission: the process by which a nucleus splits into two or more fragments. Fission may occur naturally or artificially.

Fission fragment: a product of a fission reaction with a nucleus smaller than the initial atom.

UNDERSTANDING

3 ${}^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{92}_{36}\text{Kr} + {}^{141}_{56}\text{Ba} + 3\,{}^{1}_{0}\text{n} + \text{energy}$

APPLYING

4 a ${}^{233}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{104}_{42}\text{Mo} + {}^{126}_{50}\text{Sn} + 4\,{}^{1}_{0}\text{n}$

b i $\Delta m = 0.194$ u

ii $\Delta m = 3.220 \times 10^{-28}$ kg

c $E = 2.898 \times 10^{-11}$ J

5 a 51

b ${}^{239}_{94}\text{Pn} + {}^{1}_{0}\text{n} \rightarrow {}^{104}_{43}\text{Tc} + {}^{133}_{51}\text{Sb} + 3\,{}^{1}_{0}\text{n}$

c $\Delta m = 3.154 \times 10^{-28}$ kg

d $E = 2.8386 \times 10^{-11}$ J

8.4 SECTION REVIEW

REMEMBERING

1

NUCLEAR REACTOR COMPONENT	ROLE IN THE REACTOR
Moderator	Light elements that slow down fast neutrons, enabling further nuclear reactions.
Control rods	Rods of neutron-absorbing materials, such as boron-10, used to reduce the number of free neutrons and to control the rate of a nuclear reaction.
Reactor vessel	High nucleon number (dense) material that reflects neutrons back into the reactor sample.
Coolant	A temperature control mechanism transferring kinetic heat energy from within the reactor to outside of the reactor.

2 Slow 'thermal' neutrons: neutrons that have been slowed through collisions with lighter elements (the moderator) to enable their capture within the nucleus of larger fissile elements.

UNDERSTANDING

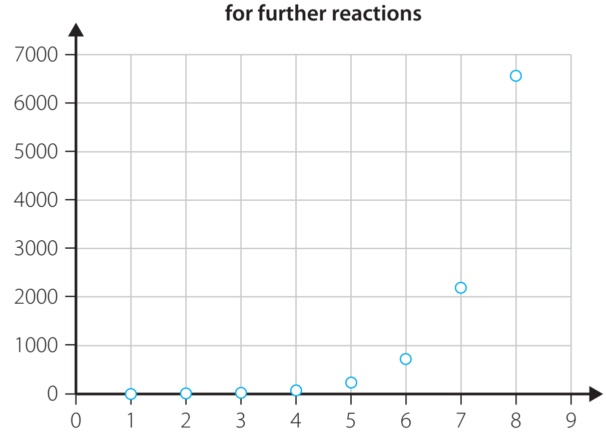
3 Control rods contain 'neutron poisons' – elements that absorb neutrons so they cannot take part in successive nuclear reactions. Control rods may be inserted or removed from the reactor vessel to control the rate of nuclear reactions occurring.

APPLYING

4 Nuclear fission reactions typically produce multiple neutrons – each successive reaction enables more reactions to occur. This is shown in the table of successive reactions and the exponential graph of reactions over time.

SUCCESSIVE REACTIONS	NUMBER OF NEUTRONS AVAILABLE FOR FURTHER REACTIONS
1	$3^1 = 3$
2	$3^2 = 9$
3	$3^3 = 27$
4	$3^4 = 81$
5	$3^5 = 243$
6	$3^6 = 729$
7	$3^7 = 2187$
8	$3^8 = 6561$

Number of neutrons available for further reactions



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REFLECTING

5 Nuclear power generation in Australia

POSITIVE	NEGATIVE
Environmental – nuclear power plants to not release greenhouse gases and emit fewer radioactive materials into the atmosphere than traditional coal-burning power plants.	Environmental – nuclear disasters, although rare, have catastrophic environmental and public health effects due to dangerous levels of radioactivity.
Economy and efficiency – nuclear power electricity generating plants are in excess of 90% efficient, operate continuously and are cost effective.	Non-renewable – Australia has access to significant renewable energy sources that are not finite and that pose no risk to the environment or climate change.
Abundance of nuclear fuel – Australia has 33% of the world's uranium deposits.	Abundance of alternative fuels – Australia has extensive coal and natural gas resources.

8.5 SECTION REVIEW

REMEMBERING

1 Nuclear fusion is the process of joining two or more nucleons together to form a new atom. Fusion occurs for lighter elements ($Z < 56$) and is accompanied by the release of energy.

2 Nuclear fusion

APPLYING

3 ${}^{2}_{1}\text{H} + {}^{2}_{1}\text{H} \rightarrow {}^{3}_{2}\text{He} + {}^{1}_{0}\text{n} + \text{energy}$

4 Nuclear fusion requires the joining of two or more elements to form a new atom, with an accompanying release of energy.

Nuclear fission requires the splitting of an atom into two or more fission fragments, with an accompanying release of energy.

8.6 SECTION REVIEW

REMEMBERING

1 Nuclear waste examples

High level	Spent fuel rods
Medium level	Pipes, gauges, fuel containers
Low level	Protective clothing, water from washing of protective equipment

2 Spent nuclear fuel must be stored in shielded containers and cooled to prevent the escape of radiation and overheating.

REFLECTING

3 Authority, accuracy, objectivity, currency and coverage

8.7 SECTION REVIEW

REMEMBERING

1 $c = 3.00 \times 10^{8}\ \text{m s}^{-1}$

2 $E = \Delta mc^2$

E = energy (J)

Δm = mass defect (kg)

c = speed of light (m s^{-1})

UNDERSTANDING

3 a Iron, mass number 56; 8.7 MeV per nucleon

b Bromine, mass number 80; 8.6 MeV per nucleon

c Oxygen, mass number 16; 8.0 MeV per nucleon

d Uranium, mass number 238; 7.5 MeV per nucleon

e Helium, mass number 4; 7.2 MeV per nucleon

4 The mass defect represents the difference in mass between an atom and its constituent parts. The energy released in a nuclear reaction is determined using the mass defect, $E = \Delta mc^2$.

APPLYING

5 $\Delta m = 2.600\,28\ \text{u} = 4.316\,465 \times 10^{-27}\ \text{kg}$

$E = 3.885 \times 10^{-10}\ \text{J}$

6 $\Delta m = 0.317\,14\ \text{u} = 5.2645 \times 10^{-28}\ \text{kg}$

$E = 4.738 \times 10^{-11}\ \text{J}$

7 $\Delta m = 0.003\,22\ \text{u} = 5.3452 \times 10^{-30}\ \text{kg}$

$E = 4.811 \times 10^{-13}\ \text{J}$

8 $\Delta m = 0.005\,49\ \text{u} = 9.1134 \times 10^{-30}\ \text{kg}$

$E = 8.202 \times 10^{-13}\ \text{J}$

CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 a Nucleon: A subatomic particle found within the nucleus, e.g. proton or neutron. Nucleons have a mass of approximately 1 amu.

b Nuclear fission: the process by which heavy nuclei ($Z > 56$) separate into fragments, with the release of energy; typically, fission fragments have quite different masses.

c Nuclear fusion: the process by which nucleons join to form a new nucleus.

Nucleosynthesis is the set of fusion reactions that lead from nucleons to a variety of nuclides. This occurs for light elements ($Z < 56$) and energy is released.

d Nuclear binding energy: The nuclear binding energy is an energy value, given in joules or megaelectron-volts, determined using the mass defect, Δm and $E = \Delta mc^2$. It represents the energy that binds the nucleus together.

e Transmutation: A nuclear transmutation is the process of transforming one element or nuclide into another, through fission or fusion. Transmutations may be natural or artificial.

2 The mass defect is the difference between the rest mass of the atom and the mass of its constituent parts. The mass defect is found within the mass–energy equivalence relationship, $E = \Delta mc^2$, and is used to determine the energy binding the nucleus together.

3 The atomic number of an atom represents the number of protons and is unique for each atom. The mass number of an atom represents the number of protons and neutrons found within the nucleus.

CATEGORY QUESTIONS

4 The electromagnetic force is of significantly greater magnitude; approximately $\times 10^{36}$ greater than the gravitational force. The range of both forces is infinite.

5 A nuclear fission chain reaction requires a critical mass of fuel source and a mechanism to control the number of neutrons taking part in successive reactions.

6 Artificial transmutations occur following the bombardment of a nucleus by a neutron or other light element. Natural transmutations occur continually and spontaneously through natural radioactive decay.

ELABORATION QUESTIONS

7 The binding energy per nucleon represents the energy provided from a nuclear reaction per nucleon (proton or neutron). This is a measure of the energy per unit of mass reacted and is more useful for comparing the efficiency of reactions.

8 The megaelectron-volt represents 1.6×10^{-13} J; values are simpler to work with.

9 The strong nuclear force is approximately $\times 10^8$ greater than the weak nuclear force, and the range of the strong nuclear force is 1000 times greater. The strong nuclear force acts to bind nucleons within the nucleus whereas the weak nuclear force acts within nucleons and is responsible for radioactive decay.

EVIDENCE QUESTIONS

10 Answers will vary depending on research conducted.

11 Answers will vary depending on research conducted.

12 Answers will vary depending on research conducted.

END-OF-CHAPTER EXAM

1 B

2 C

3 D

4 A

5 Gravitational force (weakest), weak nuclear force, electromagnetic force and strong nuclear force

6 $E = \Delta mc^2$

E = energy (J)

Δm = mass defect (kg)

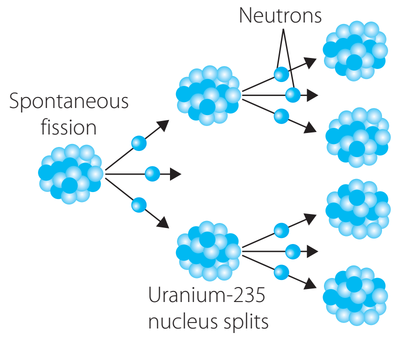
c = speed of light (m s^{-1})

7 $E = 3.6 \times 10^{16}$ J

8 U-235 has 92 protons and 235 – 92 = 143 neutrons.

9 Nuclear fission is the process of transmutation where a large parent nucleus is split into two or more smaller, daughter nuclei with an accompanying release of energy. Nuclear fusion is the process of joining two or more nuclei to form a single, large nucleus with an accompanying release of energy.

10



11 The most stable nuclide is iron-56. Xenon-140 is bigger than iron, hence is more likely to take a part in fission. Carbon-12 is smaller than iron, hence is more likely to take part in fusion.

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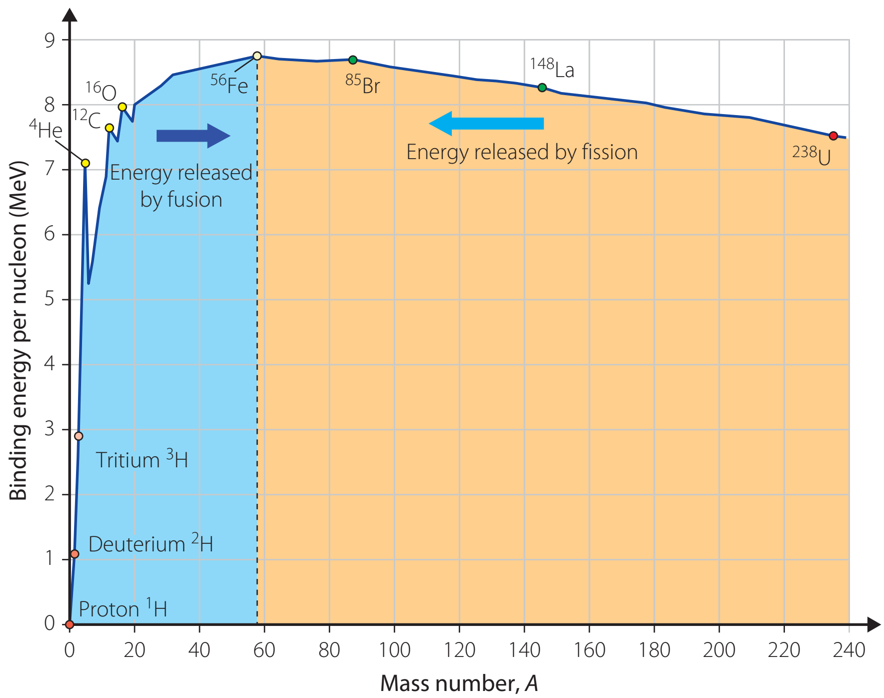


12

13 a Two neutrons

b $\Delta m = 0.1844\,\text{u}$

$\Delta m = 3.0610 \times 10^{-28}$ kg

c $E = 2.7549 \times 10^{-11}$ J

14 a Four neutrons

b $^{1}_{0}\text{n} + {}^{233}_{92}\text{U} \rightarrow {}^{104}_{42}\text{Mo} + {}^{126}_{50}\text{Sn} + 4\,^{1}_{0}\text{n}$

c $\Delta m = 0.1982\,\text{u}$

$\Delta m = 3.2901 \times 10^{-28}$ kg

d $E = 2.9611 \times 10^{-11}$ J

15 With current technology, nuclear fission – reducing greenhouse emissions from coal burning power generation.

CHAPTER 9: CURRENT, POTENTIAL DIFFERENCE AND ENERGY FLOW

9.1 SECTION REVIEW

REMEMBERING

1 a Static electricity is the build-up of electric charge on an object, typically an insulator.

b Potential energy is stored energy that has the potential to do work, such as gravitational potential, electric potential or chemical potential energy.

c An insulator is a material that inhibits the flow of electrons, such as plastic or rubber.

d A conductor is a material that allows the free flow of electrons. Metals are good electrical conductors.

2 D

UNDERSTANDING

3 Proton: $+1.6 \times 10^{-19}$ C

Neutron: no charge

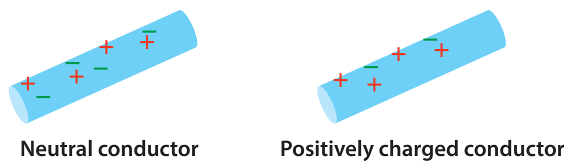
Electron: -1.6×10^{-19} C

4

	PROTON	NEUTRON	ELECTRON
Relative mass	1	1	$\frac{1}{10\,000}$
Position	Nucleus	Nucleus	Electron shell outside nucleus

APPLYING

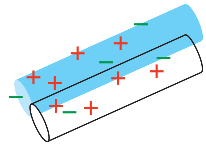
5 a



Electrons are attracted to the positively charged conductor.

b The positively charged conductor will attract the neutral conductor as the negative electrons are able to move within the material to the side closer to the positively charged rod, exerting a greater attractive force than the repulsion of the like charges.

c



Charges are shared equally across the conductors.

9.2 SECTION REVIEW

REMEMBERING

1 a False

b True

2 The law of conservation of charge states that the net charge in a system is conserved, that is, the net charge may only be increased or decreased by adding or removing charges from outside of the system.

UNDERSTANDING

3 Kirchhoff's current law (first law) states that the total current arriving at a junction within an electric circuit is equal to the total current leaving the junction.

APPLYING

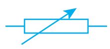
4 a $I_3 = 90\,\text{mA}$

b $I_1 = 2.25\,\text{A}$

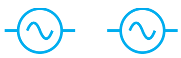
9.3 SECTION REVIEW

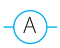
REMEMBERING

1 Electromotive force, EMF, is a source of potential energy per charge, or voltage.

2 a 

b 

c 

d 

e 

UNDERSTANDING

3 An electromotive force (e.g. battery) and typically a load (e.g. lamp, or device to transform electric potential energy into other forms) connected by conducting wires.

4 Batteries store energy by increasing the electric potential by placing a large number of electrons near each other at one terminal of the battery. This requires charge to be moved to this terminal.

REFLECTING

5 The charging of a phone battery does not introduce more charge – it simply relocates the charge from one terminal to another.

9.4 SECTION REVIEW

REMEMBERING

1 a Conventional current is the established convention where electricity is considered as the flow of (hypothetical) positive charge.

b Alternating current, AC, is the flow of charge that changes direction periodically, typically at 50 hertz.

c Potential difference, measured in volts, describes the potential energy available per unit of charge.

d Power is defined as the rate of energy transformation (or work done) per unit of time, $p = \frac{W}{t}$

2 $3.6 \times 10^6\ \text{J} = 1.0\,\text{kWh}$

UNDERSTANDING

3 The kWh is a more convenient unit of measurement for household power than the joule.

APPLYING

4 $q = 7.5\,\text{A s}$ or $7.5\,\text{C}$

5 $W = 180\,\text{J}$

6 a $I = 0.94\,\text{A}$

b $P = 225\,\text{W}$

7 a $W = 19\,\text{MJ}$

b 36.9 kWh

9.5 SECTION REVIEW

REMEMBERING

1 Step 1: Read the question carefully and try to understand the scenario.

Step 2: Organise the information, particularly the values and units provided.

Step 3: Sketch a diagram.

Step 4: Consider what formula may be applied.

Step 5: Verify the units and perform any conversions required.

2 $q = 1.6 \times 10^{-19}\ \text{C}$

UNDERSTANDING

3 6.25×10^{18} particles

4 A potential difference leads to an attraction of electrons at the positive terminal of the conducting loop, leading to the flow of electrons.

APPLYING

5 $q = 20\ \text{C}$

6 5.0×10^{17} electrons

7 0.1 A

ANALYSING

8 a 1920 W

b 41.5 MJ

9 37.5 C, 2.35×10^{20} charges

10 27 J

9.6 SECTION REVIEW

REMEMBERING

1 Kirchhoff's voltage law: for any closed loop in an electric circuit, the sum of the potential differences must be zero.

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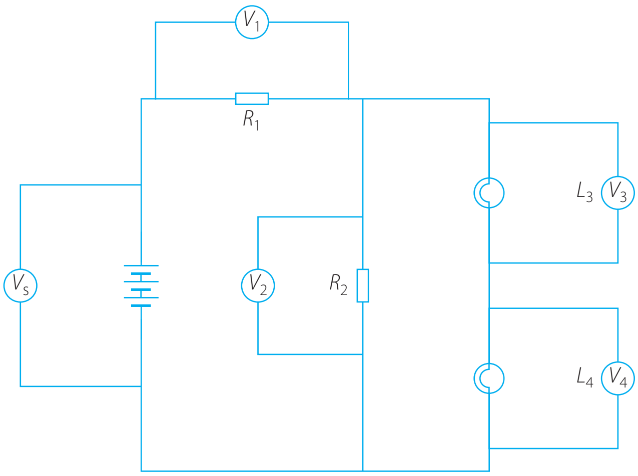
2 The law of conservation of electric charge states that the net charge in a system can only be increased or decreased by adding or removing charges from outside of the system, i.e. all charge is conserved within a closed system.

UNDERSTANDING

3



L_3 and L_4 are in series with each other.

R_2 and L_3 and L_4 are in parallel paths.

APPLYING

4 $V_2 = V_3 = 3\,V$

5 $V_S = 14\,V$

6 $V_2 = 14\,V$ and $V_3 = V_4 = 7\,V$

CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 a Proton: a positively charged subatomic particle found within the atomic nucleus; $q_p = +1.6 \times 10^{-19}$ C.

b Neutron: a neutral subatomic particle found within the atomic nucleus. The mass of a neutron is approximately the same as that of a proton.

c Electron: a negatively charged subatomic particle and the primary charge carrier in conductors; $q_e = -1.6 \times 10^{-19}$ C.

d Metal lattice: a regular arrangement of large numbers of metal atoms that allows free electrons to move readily.

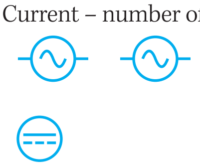
e Current: the rate of flow of charge, that is, charge per unit time; measured in amperes, A. $I = \frac{q}{t}$

f Voltage: the electric potential, measured in volts, V. A measure of the energy available per unit charge.

2 Voltage – energy per charge

Current – number of charges per unit of time

3



CATEGORY QUESTIONS

4 Static electricity is the build-up of electric charge on insulators, hence the charges are at rest. Current electricity typically occurs through conducting materials, such as metal wires, that allow the free flow of electrons.

5 An ammeter – connected in series.

6 Conductors allow the flow of electric charge. Insulators inhibit the flow of electric charge.

ELABORATION QUESTIONS

7 The Rutherford–Bohr model of the atom places the negatively charged electrons in varying shells outside of the nucleus thereby allowing electrons to readily flow in a conductor with an applied potential difference.

8 Electric current is the flow of the negative charge carrier, the electron. Conventional current is also the flow of charge, but is defined by convention as the flow of a hypothetical positively charged particle.

9 Potential difference is a measure of the amount of energy per unit charge, so regardless of whether a current of flowing electrons splits down parallel paths, each individual electron has the same amount of energy.

EVIDENCE QUESTIONS

10 Answers will vary

11 Answers will vary

12 Answers will vary

END-OF-CHAPTER EXAM

1 D

2 B

3 C

4 C

5 2.0 A away from the junction

6 $V_1 = 0.75\,V$

7 Electrons flow from the negative terminal to the positive terminal.

8 Positive charge.

9 $0.5\,C = 3.125 \times 10^{18}$ electrons

10 $P = \frac{W}{t} = V \times I;\ V = I \times R$

11 $W = 360\,000\,J = 360\,kJ = 0.1\,kWh$

12 $V = 1.5\,V$

13 Emilie is correct. All matter is made of atoms and the subatomic positive protons and negative electrons. A neutral object has equal numbers of positive and negative charges.

14 a $q = 20\,C$

b $W = 12\,J$

c 40 s

15 The negative charges in the neutral conducting rod are able to move, hence they move closer to the positively charged rod. As they are closer their electrostatic attraction is greater

than the repulsion between the positively charged protons at a greater distance, hence the two rods attract.

CHAPTER 10: RESISTANCE

10.1 SECTION REVIEW

REMEMBERING

1 a Metals, e.g. copper

b Water

c Rubber

d Silicon

2 $R = \frac{\rho \times \ell}{A}$ or $\rho = \frac{R \times A}{\ell}$

UNDERSTANDING

3 $R \propto \ell$ as charges moving through a greater length of conductor meet greater opposition to their flow due to the greater length.

4 Resistance is the opposition to flow of electrical charge in a material, measured in ohms, Ω.

APPLYING

5 $\rho = 1.25 \times 10^{-8}\ \Omega.\text{m}$

6 $\rho = 1.8 \times 10^{-8}\ \Omega.\text{m}$, $l = 0.50\,\text{m}$, $A = 1 \times 10^{-6}\ \text{m}^2$, $R = 9.0 \times 10^{-3}\ \Omega$

10.2 SECTION REVIEW

REMEMBERING

1 $R = \frac{V}{I}$, the law relating the current and voltage through a conductor as directly proportional, $V \propto I$

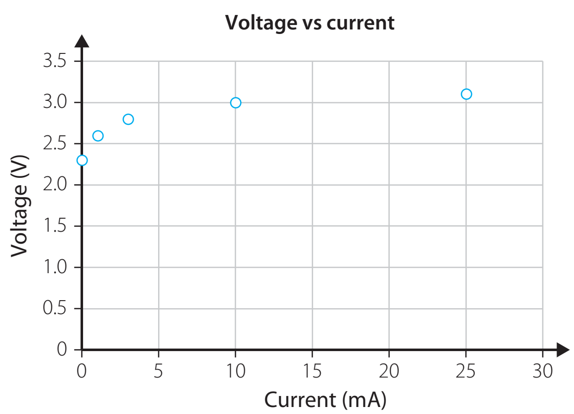
2 Ohmic device: ceramic resistor; Non-ohmic device: light emitting diode (LED)

UNDERSTANDING

3 Ohmic materials demonstrate a proportional relationship between the current and voltage, that is $V \propto I$. Non-ohmic materials demonstrate a non-linear relationship between the voltage across and current through the material, that is, the resistance varies in non-ohmic materials.

APPLYING

4 a



b The device is non-ohmic. The relationship between current and voltage is non-linear.

c $R = \frac{V}{I}$

$R = \frac{3\,\text{V}}{10 \times 10^{-3}\ \text{A}}$

$R = 300\,\Omega$

10.3 SECTION REVIEW

REMEMBERING

1 Random error: error in timing using a stopwatch.

Systematic error: calibration error in electronic mass scales.

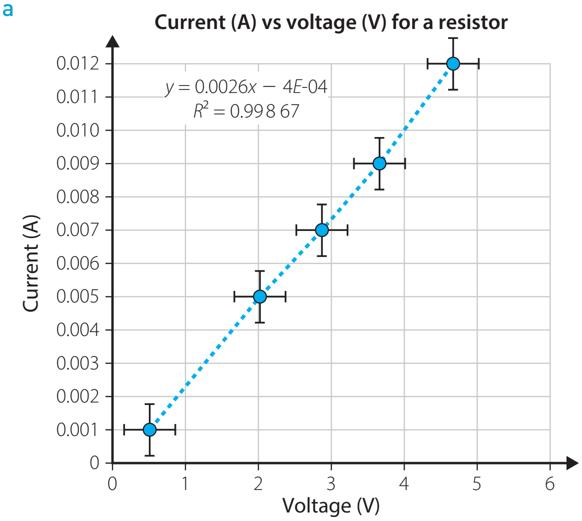
2 Error bars indicate the uncertainty associated with each measurement and assist in determining if the line of best fit is a precise model of the relationship.

UNDERSTANDING

3 A random error is typically seen as values fluctuating on either side of the expected values, that is, as a two-sided error. A systematic error is typically seen as a one-sided error with values either all below or all above the expected values.

ANALYSING

4 a



Trendline label should read: $y = 0.0026x - 4E - 04$

Correlation label should read: $R^2 = 0.99867$

b The device is ohmic, with a linear relationship between the current and voltage.

c The resistor is ohmic.

$R = 382.5\ \Omega$

This value lies within $390\ \Omega \pm 19.5\ \Omega$ (5%) so is accurate.

10.4 SECTION REVIEW

REMEMBERING

1 a Ω

b Ω.m

c A

d V

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2 A line of best fit is adequately modelled using a minimum of five points of data to ascertain the nature of the relationship (linear, quadratic, inverse, etc.)

UNDERSTANDING

3 Random error: multiple numbers of trials and averaging values.

Parallax error: positioning of the observer or device perpendicular to the measuring device.

Systematic error: zeroing or calibrating the measuring device.

CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 a Resistance is the opposition to the flow of electrical charge in a material, measured in ohms, Ω.

b A conductor is a material that allows the flow of electrons with very little resistance, e.g. metals.

c An insulator is a material that inhibits the flow of electrons, e.g. plastic.

d A semiconductor is a material that conducts electrical charge at varying levels depending on temperature.

2 $m = \frac{\Delta I}{\Delta V} = \frac{1}{R}$; the inverse of the gradient is the resistance.

3 Resistance is affected by length, cross-sectional area and resistivity.

CATEGORY QUESTIONS

4 Ohmic devices exhibit a linear relationship between current and voltage, $V \propto I$.

Non-ohmic devices do not.

5 Length (m), cross-sectional area (m^2) and resistivity (Ω.m)

6 Gold is a good conductor with a large number of free conducting electrons in its metal lattice.

Timber is a poor conductor with few conducting electrons.

Rubber is an insulator that has tightly bound electrons.

Silicon is a semiconductor that can be 'doped' to vary its conducting properties.

ELABORATION QUESTIONS

7 Random errors typically occur as values both above and below the expected values.

8 The resistance of resistors increases with temperature, hence a decrease in temperature would decrease the resistance.

9 Error bars show the uncertainty above and below a measured value. Error bars can be used to assess the precision of data.

EVIDENCE QUESTIONS

10 Answers will vary depending on research conducted.

11 Answers will vary depending on research conducted.

12 Answers will vary depending on research conducted.

END-OF-CHAPTER EXAM

1 C
2 D
3 D
4 C

5 ℓ, A or ρ

6 Conductor

7 $\rho = 1.25 \times 10^{-5}$ Ω.m

8 $R = 0.009$ Ω

9 $V \propto I$ for ohmic resistors, hence they have a constant resistance. Non-ohmic resistors have varying resistance.

10 A greater cross-sectional area provides a larger number of free conducting electrons per unit length.

11 6.67 Ω

12 432 V

13 a Diameter A: diameter B is: 1:2

b $I_A = 1$ A, $I_B = 0.5$ A

14 $m = \frac{\Delta I}{\Delta V} = 0.002\ 59 = \frac{1}{R}$

$R = 386.3$ Ω

The resistance falls within the 5% tolerance.

CHAPTER 11: CIRCUIT ANALYSIS AND DESIGN

11.1 SECTION REVIEW

REMEMBERING

1 Power is a measure of the rate of energy transformation measured in watts, W.

2 Ohm's law is the constant relationship between current and voltage, $V \propto I$, as expressed in the formula $V = I \times R$

UNDERSTANDING

3 $P = V \times I$

$P = I^2 \times R$

$P = \frac{V^2}{R}$

4 a 130 mA

b 6000 W

c 0.3×10^6 W or 3×10^5 W

APPLYING

5 $P = 38.4$ W

11.2 SECTION REVIEW

APPLYING

1 a 3.33 A
b 72.1 Ω
c 800 W
d 960 000 J

2 a 0.5 A
b 480 Ω
c 120 W
d 43 200 J

ANALYSING

3 a 0.83 A
b 288 Ω
c 200 W
d 96 000 J

4 a 9.17 A

b 26.2 Ω

c 2200 W

d 47.5 MJ

11.3 SECTION REVIEW

REMEMBERING

1 a 

b 

c 

d 

e 

2 Lamp  

Resistor  

Switch  

11.4 SECTION REVIEW

REMEMBERING

1 Voltage and electromotive force (EMF)

2 a shared

b equivalent

UNDERSTANDING

3 A series circuit provides a single path for current to flow. The current is equivalent through all loads and the potential is divided across the loads.

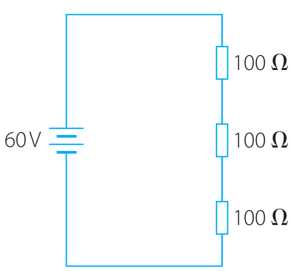
A parallel circuit provides multiple paths for the current to flow. The current splits along the parallel paths and the potential drop is equivalent across each parallel path.

4 $R_T = R_1 + R_2 + R_3$

5 $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$

APPLYING

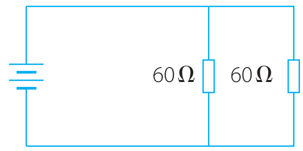
6



$R_T = 300\,\Omega$

$I_T = 0.2\,A$

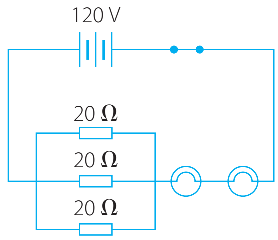
7



$\frac{1}{R_T} = \frac{1}{60} + \frac{1}{60}$

$R_T = 30\,\Omega$

8



REFLECTING

9 Draw the complete, labelled circuit.

Determine parallel and series components.

Calculate the equivalent resistances for series components and parallel components.

Simplify and re-draw the circuit.

Calculate the currents and voltages using Ohm's law.

11.5 SECTION REVIEW

REMEMBERING

1 Kirchhoff's current law states that the total current arriving at a junction within an electric circuit is equal to the total current leaving the junction.

Kirchhoff's voltage law states that for any closed loop in an electric circuit, the sum of the potential differences must be zero.

2 $R = \frac{V}{I}$

UNDERSTANDING

3 $V_T = I_T \times R_T$ only applies for the total current and total resistance.

APPLYING

4 a 160 Ω

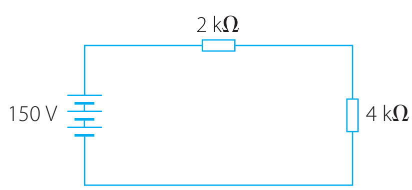
b 10 Ω

11.6 SECTION REVIEW

ANALYSING

1 a 6 kΩ

b



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c 0.025 A

d $V_{2k\Omega}$: 50 V

$V_{6k\Omega}$: 100 V

$V_{12k\Omega}$: 100 V

e $I_{2k\Omega}$: 0.025 A

$I_{6k\Omega}$: 0.017 A

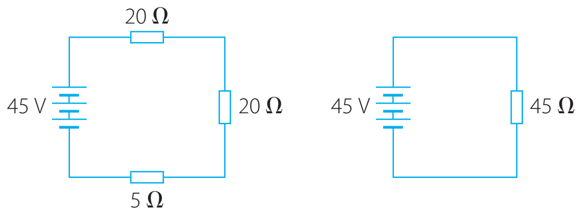
$I_{12k\Omega}$: 0.0083 A

2 a $R_{eq} = 20\,\Omega$

b $R_{eq} = 10\,\Omega$

3 a $R_{eq} = 45\,\Omega$

b Draw the correct series circuit for the parallel arrangement, then redraw the circuit showing the equivalent circuit for the series arrangement.



c 1.0 A

d $V_{20\Omega}$: 20 V, $V_{30\Omega}$: 20 V, $V_{60\Omega}$: 20 V, $V_{5\Omega}$: 5 V

e $I_{20\Omega}$: 1.0 A, $I_{30\Omega}$: 0.67 A, $I_{60\Omega}$: 0.33 A, $I_{5\Omega}$: 1.0 A

4 $R_1 = 20\,\Omega$, $V_T = 12.8$ V

5 a $R_{eq} = 28.75\ \Omega$

b $V_T = 46$ V

11.7 SECTION REVIEW

REMEMBERING

1 240 V, 50 Hz

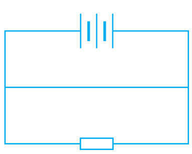
UNDERSTANDING

2 Residual current device – an earth-leakage protection device.

Circuit breaker – electromechanical switch that protects from an overload.

Fuse – a temperature-dependent safety protection device.

3 A short circuit is a bypass within a circuit where the current flows through a less resistive pathway.



APPLYING

4 Electrical circuits have maximum current loads for safety, hence the multiple circuits are required.

CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 a Potential difference – potential energy per unit charge, measured in volts.

b Current – rate of flow of electric charge, measured in amperes.

c Ohmic material – materials that obey Ohm's law, $R = \frac{V}{I}$.

d Power loss – a measure of the rate of energy loss to other forms, measured in watts.

2 $P = V \times I$

$P = I^2 \times R$

$P = \frac{V^2}{R}$

3 Voltage, resistance and current

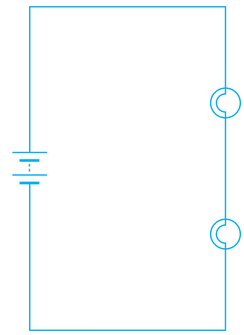
CATEGORY QUESTIONS

4 Resistors in series add to a larger total equivalent resistance.

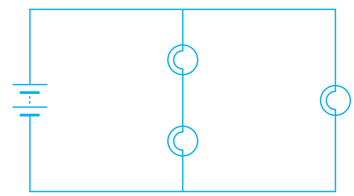
Resistors in parallel reduce the total equivalent resistance.

5 Parallel circuits allow a device to fail without impacting on other devices within the circuit.

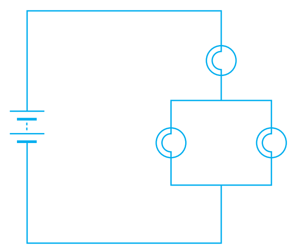
6 Series circuit example



Parallel circuit example



Combination circuit example



ELABORATION QUESTIONS

7 Kirchhoff's current law states that the current arriving at a junction within a circuit is equal to the total current leaving the junction and current is the charge per unit of time.

8 $P = I^2 \times R$. If the current is decreased, the power also decreases.

9 A short circuit may occur due to bare wires touching or a conductor joining sections of a circuit bypassing a load.

EVIDENCE QUESTIONS

10 In a series circuit the flow of charge is constant through all devices. In a parallel circuit, the flow of charge is divided between the parallel circuits. Each individual charge provides its potential (voltage) across its parallel path.

11 a 4.17 A

b 57.6 Ω

c 1000 W

d 2.88×10^7 J

12 a 45 Ω

b 5 Ω

END-OF-CHAPTER EXAM

1 A

2 C

3 B

4 C

5 a 

b 

c 

d 

6 Ohm's Law

7 $R_{series} = 10\,\Omega$; $R_{parallel} = 2.5\,\Omega$

$I_{series} = 2$ A; $I_{parallel} = 8$ A

8 $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$

9 Ohmic resistors demonstrate a constant proportion of $V \propto I$.

Non-ohmic resistors do not obey Ohm's law, $R = \frac{V}{I}$

10 $R_T = 242.9\,\Omega$

$V_T = 20$ V

$I_T = 0.082$ A

$I_{100\Omega} = 0.082$ A

$I_{200\Omega} = 0.059$ A

$I_{500\Omega} = 0.023$ A

$V_{100\Omega} = 8.2$ V

$V_{200\Omega} = 11.8$ V

11 A short circuit occurs when a load in a circuit is bypassed by a conducting pathway such as by crossing exposed wires.

12 Step 1: Determine which components are connected in series, and which are in parallel.

Step 2: Calculate the equivalent resistance across each parallel section.

Step 3: Simplify the circuit by redrawing it, replacing the parallel resistors with a single, equivalent resistor.

Step 4: Calculate the total current in the circuit using the total voltage, using Ohm's law.

Step 5: Use Kirchhoff's current and voltage laws, as well as Ohm's law, to determine the current through and the voltage across all components.

Step 6: Calculate any power dissipations from the known values of current, voltage and resistance.

Step 7: Select a value/s to substitute back into the original problem to check your solutions.

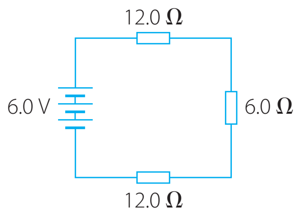
13 a 3.2 Ω

b 2.4 Ω

c 4 Ω

d 6 Ω

14 a



b 30 Ω

c 0.2 A

d $V_{12\Omega} = 2.4$ V, $V_{6\Omega} = 1.2$ V

15 a $I = 1.0$ A

b $R_T = 12\,\Omega$

c 2 V

d 4 V

e 0.5 A

CHAPTER 12: VECTORS

12.1 SECTION REVIEW

REMEMBERING

1 Scalar: quantity specified by magnitude only

Vector: quantity that has magnitude and direction (from Greek 'to convey')

Distance: length

Displacement: position relative to another position; the difference between two positions specified with respect to an origin; the straight-line distance between the current position of a particle in a wave and its mean position

2 a see Table 12.1.1

b see Table 12.1.2

3 a changes magnitude

b changes magnitude and reverses direction

UNDERSTANDING

4 Both have magnitude (length); displacement includes length and direction

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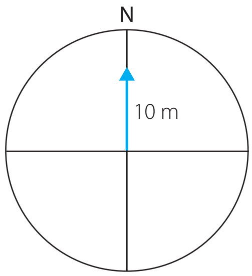
5 Distance tells you how far in total; displacement tells you where you are relative to some other position

6 Both specify direction using a compass and angles; quadrant angles range from 0° to 90°, true bearings range from 0° to 360°

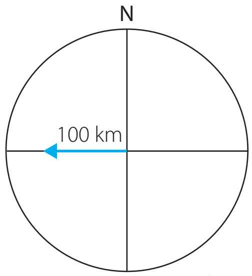
APPLYING

7 a



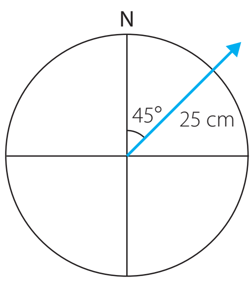
1 cm represents 10 m

b



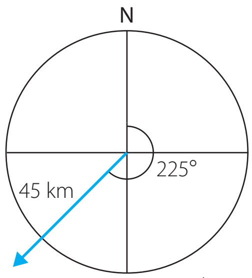
1 cm represents 100 km

c



1 cm represents 10 cm

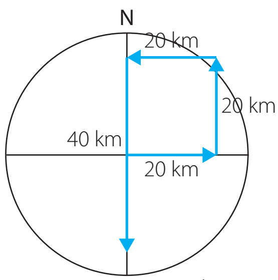
d



1 cm represents 10 km

ANALYSING

8 a



1 cm represents 10 km

b 100 km

c 20 km, S

9 Division is multiplication by the inverse of the divisor

12.2 SECTION REVIEW

REMEMBERING

1 a $\vec{s} = \vec{d}_2 - \vec{d}_1$

b $s = \left|\vec{d}_2 - \vec{d}_1\right|$

UNDERSTANDING

2 Magnitude is the size of the vector displacement

APPLYING

3 a $^{-}6\,\text{km} + 5\,\text{km} = {}^{-}1\,\text{km}$

b $4\,\text{m} + 5\,\text{m} = 9\,\text{m}$

c $^{-}8\,\text{cm} - 2\,\text{cm} = {}^{-}10\,\text{cm}$

d $5\,\text{m} - 2\,\text{m} = 3\,\text{m}$

e $^{-}10\,\text{km} - {}^{-}3\,\text{km} = {}^{-}7\,\text{km}$

f $2\,\text{mm} - {}^{-}3\,\text{mm} = 5\,\text{mm}$

ANALYSING

4 Each displacement from position to position has a distance as well as a direction. Each distance adds to make the total distance travelled.

EVALUATING

5 Answers will vary

CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 Scalar: one scale; vector: 2 or more scales

2 a see Key formula, page 252

b see Key formula, page 253

3 $A, \vec{A}, \tilde{A}$

CATEGORY QUESTIONS

4 a Scalar: magnitude

b Vector: magnitude and direction

ELABORATION QUESTIONS

5 Displacements are always relative to a position, even when that position is defined as zero.

6 Displacement is from start to end, including direction (63.45 m, N45°W). Distance is the individual lengths covered (90 m).

EVIDENCE QUESTIONS

7 a Answers will vary

b Answers will vary

END-OF-CHAPTER EXAM

1 A

2 C

3 A

4 magnitude

5 north

6 Scalar quantities use one scale while vector quantities use two or more scales

7 Quadrant bearings use angles from 0° to 90° related to each quarter of the compass while true bearings use angles from from 0° to 360° clockwise from north.

8 $s = \left|\vec{d}_2 - \vec{d}_1\right|$

$s = \left|{}^{-}16\,\text{cm} - 5\,\text{cm}\right|$

$s = 21\,\text{cm}$

CHAPTER 13: LINEAR MOTION

13.1 SECTION REVIEW

REMEMBERING

1 a length measure (magnitude of displacement interval)
 b length and direction measure of one position relative to another position
 c change or difference between a quantity, such as time or position
 d point at which all the mass of an object is concentrated

UNDERSTANDING

2 Each time measure assumes an agreed start time or origin of zero

3 Each displacement measure assumes a start position or origin of zero

APPLYING

4 a $7.0\,s - 3.0\,s = 4.0\,s$
 b $2.45 \times 10^{-2}\,s - 1.37 \times 10^{-2}\,s = 1.08 \times 10^{-2}\,s$

5 a $15.1\,cm + {}^{-}4.3\,m = 19.4\,m$
 b ${}^{-}784\,mm + 9.0\,mm = 793\,mm$

13.2 SECTION REVIEW

REMEMBERING

1 a Rate of change of distance at a particular moment in time.
 b Rate of change of distance taken over a measured time interval.
 c It can be ignored because the interval is so small compared to other values.

2 $[v] = \frac{[s]}{[t]} = \frac{m}{s} = m\,s^{-1}$

UNDERSTANDING

3 A negligibly small time interval is one in which all the instantaneous velocities are so similar to the average as to be considered equal

APPLYING

4 a $v_{ave} = \frac{s}{t} = \frac{|\vec{d}_2 - \vec{d}_1|}{t_2 - t_1}$

$v_{ave} = \frac{|{-90\,cm} - {}^{-}60\,cm|}{3.0\,s}$

$v_{ave} = \frac{30\,cm}{3.0\,s} = 10\,cm\,s^{-1}$

 b $\vec{v}_{ave} = \frac{\vec{s}}{t} = \frac{\vec{d}_2 - \vec{d}_1}{t_2 - t_1}$

$\vec{v}_{ave} = \frac{{}^{-}90\,cm - {}^{-}60\,cm}{3.0\,s}$

$\vec{v}_{ave} = \frac{{}^{-}30\,cm}{3.0\,s} = {}^{-}10\,cm\,s^{-1}$

ANALYSING

5 Speed relates to distance travelled, hence aircraft fuel consumption; velocity relates to displacement interval, that is, where you end up relative to the start.

REFLECTING

6 Equivalence of average and instantaneous speed over very small time intervals

13.3 SECTION REVIEW

REMEMBERING

1 a Change of velocity
 b Change of displacement over a measureable time interval
 c Rate of change of displacement at a particular time
 d Rate of change of velocity

2 Displacement and time (relative to defined origins for each)

3 a Displacement–time
 b Velocity–time

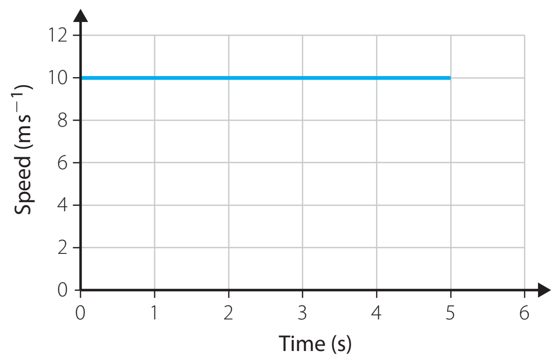
4 a Velocity–time
 b Acceleration–time

UNDERSTANDING

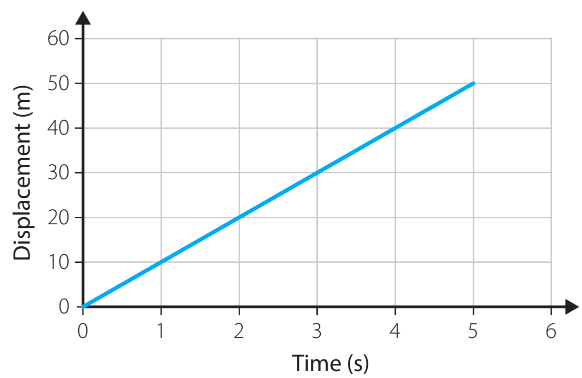
5 Displacement and time data enable velocity to be calculated which, in turn, enables acceleration to be derived.

APPLYING

6 a



 b



7 $\Delta v = 6.0\,m\,s^{-2} \times 3.0\,s = 18\,m\,s^{-1}$

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ANALYSING

8 a i $s = 80\,\text{km}\,\text{h}^{-1} \times 0.5\,\text{h} = 40\,\text{km}$

ii $s = 40\,\text{km} + 60\,\text{km}\,\text{h}^{-1} \times 0.75\,\text{h}$

$s = 40\,\text{km} + 45\,\text{km} = 85\,\text{km}$

b $v_{ave} = \dfrac{85\,\text{km}}{1.25\,\text{h}} = 68\,\text{km}\,\text{h}^{-1}$

REFLECTING

9 A model represents the real thing. Graphs represent real motion: position, velocity and acceleration of objects as time passes. Each can be used to derive related quantities by reference to gradient and areas: v from s-t (gradient); s and a from v-t (area; gradient); v from a-t (area)

13.4 SECTION REVIEW

REMEMBERING

1 a $\vec{a}$ = acceleration; $\vec{v}$ = velocity change; t = time change

b direction of velocity change, $\vec{v}$

2 (metres per second) per second

3 velocity change

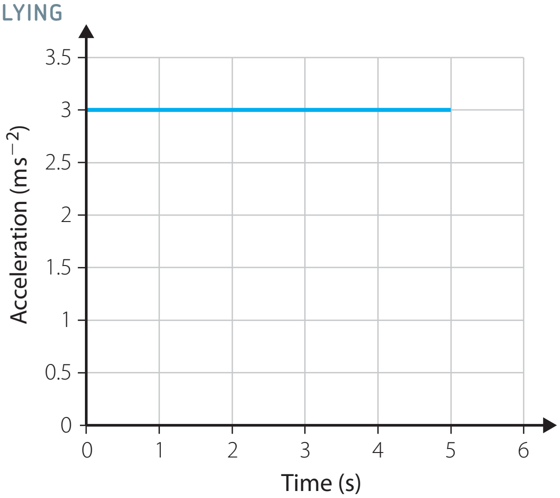
UNDERSTANDING

4 By its gradient

5 Final velocity is less in magnitude (more negatively directed) than initial velocity

APPLYING

6 a



b $v = at$

$v_f - 5.0\,\text{m}\,\text{s}^{-1} = 3.0\,\text{m}\,\text{s}^{-2} \times 4.0\,\text{s}$

$v_f = 5.0\,\text{m}\,\text{s}^{-1} + 12\,\text{m}\,\text{s}^{-1}$

$v_f = 17\,\text{m}\,\text{s}^{-1}$

c In any 1 s time interval, the speed increases by $3.0\,\text{m}\,\text{s}^{-1}$.

ANALYSING

7 The train is travelling in the same positive direction, but slowing from a greater to a lesser speed. This makes the velocity interval, hence acceleration, negative.

REFLECTING

8 Intervals enable gradients and areas to be calculated

13.5 SECTION REVIEW

REMEMBERING

1 Type of graph; axis and scale; gradient; area

2

TYPE OF GRAPH	GRADIENT REPRESENTS	AREA REPRESENTS
Displacement–time	Velocity	(-)
Velocity–time	Acceleration	Displacement interval
Acceleration–time	(-)	Velocity change

UNDERSTANDING

3 A gradient is the ratio of intervals: velocity (displacement interval: time interval); acceleration (velocity interval: time interval)

4 An area is the product of two intervals: displacement (velocity interval × time interval); velocity interval (acceleration × time interval)

APPLYING

5 a 200 m

b i $v = \dfrac{s}{t}$

$v = \dfrac{600\,\text{m} - 200\,\text{m}}{5.0\,\text{min} \times 60\,\text{s}\,\text{min}^{-1}}$

$v = 1.3\,\text{m}\,\text{s}^{-1}$

ii $\vec{v} = \dfrac{\vec{s}}{t}$

$\vec{v} = \dfrac{{}^{-}300\,\text{m} - 600\,\text{m}}{(25.0\,\text{min} - 15.0\,\text{min}) \times 60\,\text{s}\,\text{min}^{-1}}$

$\vec{v} = {}^{-}1.5\,\text{m}\,\text{s}^{-1}$

c $s = |\vec{d}_2 - \vec{d}_1| + |\vec{d}_3 - \vec{d}_2| + |\vec{d}_4 - \vec{d}_3|$

$s = |600\,\text{m} - 200\,\text{m}| + |{}^{-}300\,\text{m} - 600| + |0\,\text{m} - {}^{-}300\,\text{m}|$

$s = 1600\,\text{m}$

6 a $v_{20\,\text{s}} = \dfrac{20}{25} \times 8.0\,\text{m}\,\text{s}^{-1} = 6.4\,\text{m}\,\text{s}^{-1}$

$s_{20\,\text{s}} = \dfrac{1}{2} \times 6.4\,\text{m}\,\text{s}^{-1} \times 20\,\text{s}$

$s_{20\,\text{s}} = 64\,\text{m}$

b $s = \text{area} = \dfrac{1}{2} \times 8.0\,\text{m}\,\text{s}^{-1} \times 25\,\text{s}$

$+ 8.0\,\text{m}\,\text{s}^{-1} \times (75\,\text{s} - 25\,\text{s}) + \dfrac{1}{2} \times 8.0\,\text{m}\,\text{s}^{-1} \times 12\,\text{s}$

$s = 548\,\text{m}$

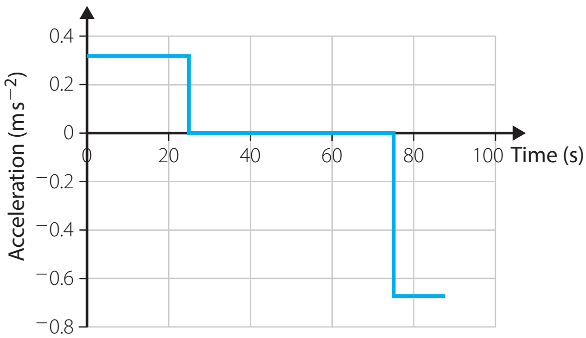
c i $a = \dfrac{8.0\,\text{m}\,\text{s}^{-1} - 0\,\text{m}\,\text{s}^{-1}}{25\,\text{s}}$

$a = 0.32\,\text{m}\,\text{s}^{-2}$

ii $a = \dfrac{0\,\text{m}\,\text{s}^{-1} - 8.0\,\text{m}\,\text{s}^{-1}}{12\,\text{s}}$

$a = {}^{-}0.67\,\text{m}\,\text{s}^{-2}$

d



e $s = \text{area}$

$\frac{1}{2} \times 8.0\,\text{m}\,\text{s}^{-1} \times 25\,\text{s} + 8.0\,\text{m}\,\text{s}^{-1} \times (t - 25\,\text{s}) = 300\,\text{m}$

$100\,\text{m} + 8.0\,\text{m}\,\text{s}^{-1} \times (t - 25\,\text{s}) = 300\,\text{m}$

$8.0\,\text{m}\,\text{s}^{-1} \times (t - 25\,\text{s}) = 200\,\text{m}$

$t - 25\,\text{s} = \dfrac{200\,\text{m}}{8.0\,\text{m}\,\text{s}^{-1}}$

$t - 25\,\text{s} = 25\,\text{s}$

$t = 50\,\text{s}$

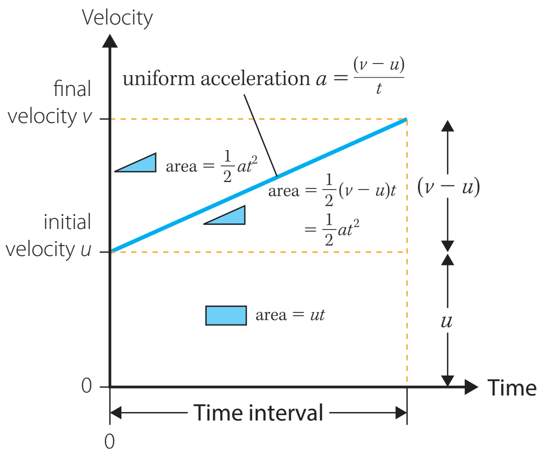
ANALYSING

7 The vehicle has travelled at the greater speed of 80 km h^{-1} for a longer period of time than the slower 70 km h^{-1}, hence it is not a simple average.

13.6 SECTION REVIEW

REMEMBERING

1 a



b s = displacement interval; u = initial velocity; v = final velocity; a = acceleration; t = time interval. For equations: see page 276

UNDERSTANDING

2 Substitute the three known values into an appropriate equation to calculate the fourth. Select an equation that will readily produce the fifth.

3 Similar: same motion is represented. Different: graphs use visual symbolism; equations use algebraic symbolism

APPLYING

4 a $v = u + at$

$a = \dfrac{v - u}{t}$

$a = \dfrac{8.0\,\text{m}\,\text{s}^{-1} - 5.0\,\text{m}\,\text{s}^{-1}}{15.0\,\text{s}}$

$a = 0.2\,\text{m}\,\text{s}^{-2}$

b $s = ut + \frac{1}{2}at^2$

$s = 5.0\,\text{m}\,\text{s}^{-1} \times 15.0\,s + \frac{1}{2} \times 0.2\,\text{m}\,\text{s}^{-2} \times (15.0\,\text{s})^2$

$s = 97.5\,\text{m}$

5 a $s = ut + \frac{1}{2}at^2$

$a = \dfrac{2s}{t^2}$ (remember $u = 0\,\text{m}\,\text{s}^{-1}$)

$a = \dfrac{2 \times 50\,\text{m}}{(2.5\,\text{s})^2}$

$a = 16\,\text{m}\,\text{s}^{-2}$

b $v^2 = u^2 + 2as$

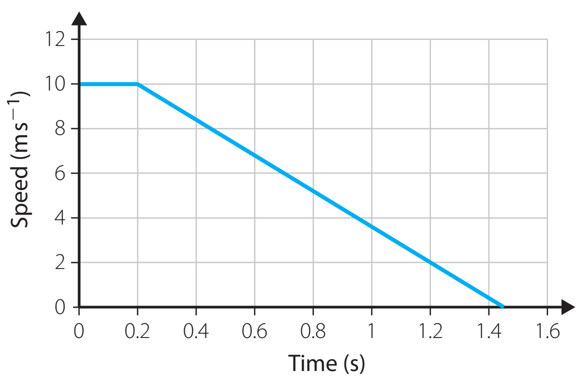
$v = \sqrt{u^2 + 2as}$

$v = \sqrt{2 \times 6.0\,\text{m}\,\text{s}^{-2} \times 50\,\text{m}}$

$v = 24.5\,\text{m}\,\text{s}^{-1}$

ANALYSING

6 a



b $s = vt$

$s = 10\,\text{m}\,\text{s}^{-1} \times 0.2\,\text{s}$

$s = 2.0\,\text{m}$

c $a = \dfrac{v}{t}$

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$t = \frac{v}{a}$

$t = \frac{0\,\text{m s}^{-1} - 10\,\text{m s}^{-1}}{{}^{-}8.0\,\text{m s}^{-2}}$

$t = 1.25$ s

d $s = \frac{1}{2} \times 10\,\text{m s}^{-1} \times 1.25\,\text{s}$

$s = 6.25$ m

e $s = 2.0\,\text{m} + 6.25\,\text{m}$

$s = 8.25$ m

REFLECTING

7 Make sure to use change in displacement and change in time for s and t, respectively, not instantaneous values.

13.7 SECTION REVIEW

REMEMBERING

1 a force by the gravitational field of a mass on another mass

b rate of change of speed of one mass affected by the gravitational field of another mass

c region where the gravitational acceleration is negligibly different from $9.8\,\text{m s}^{-2}$

2 $g = 9.8\,\text{m s}^{-2}$

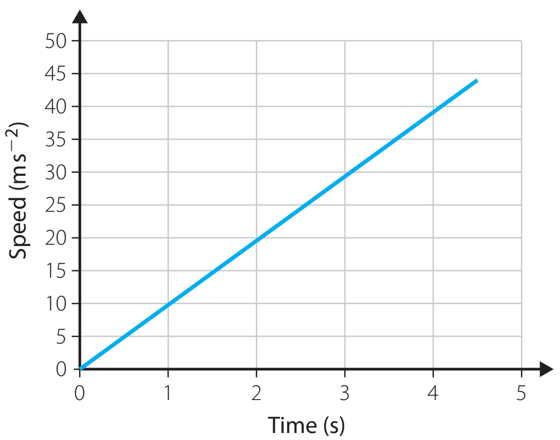
UNDERSTANDING

3 a initial movement is moving vertically towards Earth

b initial movement is moving vertically upwards from Earth

APPLYING

4 a



b $a = \text{gradient} = \frac{v}{t}$

$t = \frac{v}{a}$

$t = \frac{44.1\,\text{m s}^{-1} - 0\,\text{m s}^{-1}}{9.8\,\text{m s}^{-2}}$

$t = 4.5$ s

c $s = \frac{1}{2} \times 44.1\,\text{m s}^{-1} \times 4.5\,\text{s}$

$s = 99.2$ m

d Use *suvat* equations.

5 a 1.0 s

b $9.8\,\text{m s}^{-1}$

REFLECTING

6 a Answers will vary

b Answers will vary

CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 a Distance: Length. Displacement: Position relative to another position; the difference between two positions specified with respect to an origin; the straight-line distance between the current position of a particle in a wave and its mean position

Where:

[s] = unit of distance or displacement

[t] = unit of time

m = metre

s = second

b **Speed**: time rate of change of distance; magnitude of velocity (scalar). **Velocity**: time rate of change of displacement; speed with direction (vector).

[v] = unit of speed or velocity

[s] = unit of distance or displacement

[t] = unit of time

$\vec{v}_{av}$ = average velocity

m = metre

s = second

c **Acceleration**: Time rate of change of velocity (vector); magnitude of time rate of change of velocity (scalar); time rate of change of speed (scalar)

Where [t] = unit of time

2 For equations: see page 276.

s = displacement interval; u = initial velocity v = final velocity; a = acceleration; t = time interval.

Substitute the three known values into an appropriate equation to calculate the fourth. Select an equation that will readily produce the fifth.

3 Acceleration (gradient) and distance (area) can often be calculated easily once a v–t graph has been sketched and relevant data points identified.

CATEGORY QUESTIONS

4 a Instantaneous speed is the rate of change of distance at a particular moment in time, whereas average speed is the rate of change of distance taken over a measured time interval.

b Velocity is a measure of how fast something is travelling in a particular direction; the rate at which displacement changes. Instantaneous velocity is the velocity of a given object at a particular moment in time; whereas average velocity is the average rate of change of displacement, a vector, as time changes.

c Instantaneous acceleration is the rate of change of velocity taken at a particular moment in time, whereas average acceleration the rate of change of velocity taken over a measureable time interval.

5 Sketch *v*-*t* graphs: positive gradient for initial downwards motion at increasing distance; negative gradient for initial upwards motion at increasing distance.

ELABORATION QUESTIONS

6 Both algebraic and graphical methods may be used to find solutions to kinematics problems. Both forms are equally valid.

7 Sketch *v*-*t* graphs on same axes. Look for time when areas are the same.

8 Sketch *v*-*t* graphs with same gradient ($^-9.8\,\text{m s}^{-2}$) but different areas. Use gradient and area to find initial launch speed.

EVIDENCE QUESTIONS

9 a Sketch *v*-*t* graphs for both initial speeds. Show equal gradients from initial speed to zero. Use known areas to find time needed to come to a stop once braking begins.

b Use gradient to find assumed acceleration.

c Factor in a realistic reaction time: 2.0 s – 3.5 s.

END-OF-CHAPTER EXAM

1 D

2 D

3 D

4 B

5 D

6 C

7 velocity

8 a $\vec{s} = \vec{d}_2 - \vec{d}_1$

$\vec{s} = {}^-4.3\,\text{m} - 15.1\,\text{m}$

$\vec{s} = {}^-19.4\,\text{m}$

b $\vec{s} = \vec{d}_2 - \vec{d}_1$

$\vec{s} = \left(0.250\,\text{m} - {}^-6.75\,\text{m}\right)\times 10^{-3}$

$\vec{s} = 7.0\,\text{m}$

9 Instantaneous velocity is the velocity at a particular time; average is taken over an extended time interval.

10 point where it begins to fall

11 a $\Delta v = at$

$\Delta v = 5.0\,\text{m s}^{-1} \times \left(1.0\,\text{s} - 0.5\,\text{s}\right)$

$\Delta v = 2.5\,\text{m s}^{-1}$

b $\Delta v = at$

$v_f - 18\,\text{m s}^{-1} = 5.0\,\text{m s}^{-1} \times \left(3.0\,\text{s} - 0\,\text{s}\right)$

$v_f = 33.0\,\text{m s}^{-1}$

12 All displacements are relative to a start or origin.

13 As the object slows to a stop, it continues forward but the change in speed is negative

14 Find '*a*' from $s = ut + \frac{1}{2}at^2$; then, find '*v*' from $v = u + at$

15 $v = \frac{s}{t} = \frac{\left|\vec{d}_2 - \vec{d}_1\right|}{t}$

$v = \frac{\left|5\,\text{km} - {}^-35\,\text{km}\right|}{5\,\text{h}}$

$v = 8.0\,\text{km h}^{-1}$

$v = \frac{8.0\left(10^3\,\text{m}\right)}{1.0\left(3600\,\text{s}\right)}$

$v = 2.2\,\text{m s}^{-1}$

16 $s = \frac{u + v}{2}t$

$s = \frac{20\,\text{m s}^{-1} + 8.24\,\text{m s}^{-1}}{2} \times 1.2\,\text{s}$

$s = 16.9\,\text{m}$

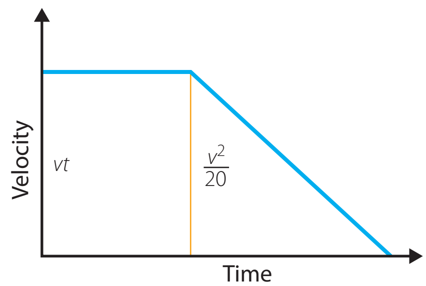
17 a 450 m b 4050 m c $0\,\text{m s}^{-2}$

18 a 45.9 m b 3.06 s c 2.20 s

19 They are both measured relative to a previous value of displacement or time

20 Motion is described using the units of m, s, m s^{-1} or m s^{-2}.

21 a and b



c 14.4 m

d Distraction and a greater reaction time increases the *vt* component *t*. A higher velocity increases both the *vt* component and the $\frac{v^3}{2}$ *a* component.

CHAPTER 14: FORCES

14.1 SECTION REVIEW

REMEMBERING

1 change speed; change direction; change both speed and direction simultaneously

2 a Force applied by one object on another, close enough to be considered to be touching

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b Force applied by one object on another, far enough apart not to be considered to be touching

c Non-contact force associated with interactions between charged particles

d Non-contact force associated with interactions between magnetic poles

e Non-contact force associated with interactions between masses

f Non-contact gravitational force

3 a applies force to a receiver object

b object that is subject to a force applied by an agent force

UNDERSTANDING

4 Two scales: magnitude; direction

5 Objects apply force externally to other objects. A force is not a property contained inside an object

6 $\vec{F}_{(\text{by B on M})}$ and $\vec{F}_{(\text{by M on B})}$

7 Mass: amount of a substance; weight: gravitational force on mass

APPLYING

8 Gravitational force is measured by measuring the normal force; scale is calibrated to read mass.

ANALYSING

9 Moon applies a smaller gravitational force on the box. The scales are read in Earth weights.

REFLECTING

10 Answers will vary

14.2 SECTION REVIEW

REMEMBERING

1 Newton's first law: v = constant if $\Sigma F = 0$;

Newton's second law: $a = \dfrac{\Sigma F}{m}$;

Newton's third law: $\vec{F}(\text{by A on B}) = \vec{F}(\text{by B on A})$

2 a Equal magnitude; opposite direction; same type; act on different objects

b Act on same object

UNDERSTANDING

3 a Resistance to force

b $w = mg$

4 Vector sum of forces acting on a single object

5 Act on different objects

APPLYING

6 Zero

ANALYSING

7 a Keep going up at constant speed

b Keep going down at constant speed

c Stay at the top

8 $a = 1\ \text{m s}^{-2}$ when $F = 1\ \text{N}$ applied on a 1 kg mass (definition)

9 F and m are independent variables

REFLECTING

10 Answers will vary

14.3 SECTION REVIEW

REMEMBERING

1 a Model of forces acting on a point particle.

b Force applied by surface on object in the direction perpendicular to the surface.

c Force applied by surface on object in the direction parallel to the surface.

2 Start at point; directed away from point; length proportional to magnitude

3 Normal force

4 a $N = F(\text{by surface on object})_{\perp}$

b $f = F(\text{by surface on object})_{\parallel}$

UNDERSTANDING

5 N affects motion perpendicular to the surface; f affects motion parallel to the surface

6 Use rules for addition and subtraction of positive and negative numbers

7 Different type (gravitational/electrostatic); act on same (not different) object

APPLYING

8 Newton's third law:

$\vec{F}(\text{by foot on surface})_{\parallel} = \vec{F}(\text{by surface on foot})_{\parallel}$; friction:

$f = \vec{F}(\text{by surface on foot})_{\parallel}$

9 $\vec{F}(\text{by person on surface})_{\perp} = \vec{F}(\text{by surface on person})_{\perp}$

$\vec{F}(\text{by person on surface})_{\perp} - w > 0$

ANALYSING

10 Friction can act as an opposing force but it can be used to propel runners, walkers and vehicles forwards

14.4 SECTION REVIEW

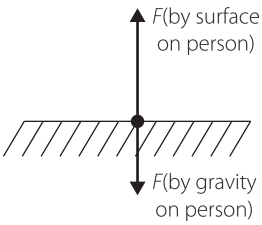
REMEMBERING

1
- Read the question carefully.
- Visualise or sketch the real situation described.
- Draw a free-body diagram.
- Identify each force acting on the object in question.
- Write each force in the form F(by A on B), or use the symbols provided in the question.
- If necessary, write the Newton's third law pair of forces.
- Identify the direction of the net force (or acceleration).
- Add any data provided in the question.

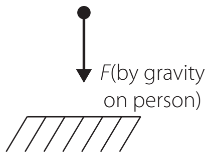
- Consider Newton's laws. Ask:
  - How does Newton's first law apply?
  - How does Newton's second law apply?
  - How does Newton's third apply?
- Set up any equations, using the symbols from the free-body diagram.
- Recall any kinematic formulas that may be useful.
- Solve the equations.
- Check to ensure the answers are those required.

UNDERSTANDING

2 a



b



APPLYING

3 a $\Sigma F = ma$

$F(\text{by kayaker}) - 57\,\text{N} = 0$

$F(\text{by kayaker}) = 57\,\text{N}$

b $a = \dfrac{\Delta v}{\Delta t} = \dfrac{4.0\,\text{m s}^{-1} - 4.0\,\text{m s}^{-1}}{\Delta t} = 0\,\text{m s}^{-2}$

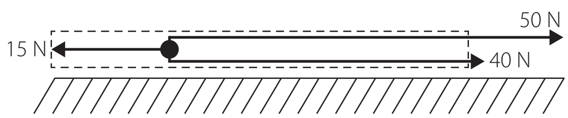
c $\Sigma F = ma$

$F(\text{by seat on kayaker})_{\perp} - w = 0$

$F(\text{by seat on kayaker})_{\perp} = 105\,\text{kg} \times 9.8\,\text{m s}^{-2}$

$F(\text{by seat on kayaker})_{\perp} = 1.03\,\text{kN}$

4 a



b $\Sigma F = 50\,\text{N} + 40\,\text{N} - 15\,\text{N} = 75\,\text{N}$

c $a = \dfrac{\Sigma F}{m}$

$a = \dfrac{75\,\text{N}}{50\,\text{kg}}$

$a = 1.5\,\text{m s}^{-2}$

5 $\Sigma F = ma$

$F - 12\,\text{N} = 36\,\text{kg} \times 4.0\,\text{m s}^{-2}$

$F = 156\,\text{N}$

6 a $a_{ave} = \dfrac{\Delta v}{\Delta t}$

$a_{ave} = \dfrac{2.5\,\text{m s}^{-1} - 0\,\text{m s}^{-1}}{125 \times 10^{-3}\,\text{s}}$

$a_{ave} = 20\,\text{m s}^{-2}$

b $\Sigma F = ma$

$\Sigma F = 70\,\text{kg} \times 20\,\text{m s}^{-2}$

$\Sigma F = 1400\,\text{N}$

c $F(\text{by platform on diver}) - w = 1400\,\text{N}$

$F(\text{by platform on diver}) = 1400\,\text{N} + 70\,\text{kg} \times 9.8\,\text{m s}^{-2}$

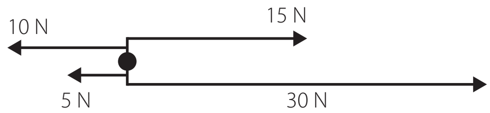
$F(\text{by platform on diver}) = 2086\,\text{N}$

By Newton's third law:

$F(\text{by platform on diver}) = F(\text{by diver on platform})$

$F(\text{by diver on platform}) = 2086\,\text{N}$

7 a



b $\Sigma F = 15\,\text{N} + 30\,\text{N} - 10\,\text{N} - 5\,\text{N}$

$\Sigma F = 30\,\text{N}$

c $a = \dfrac{\Sigma F}{m}$

$a = \dfrac{30\,\text{N}}{45\,\text{kg}}$

$a = 0.67\,\text{m s}^{-2}$

8 a Acceleration:

$v^2 = u^2 + 2as$

$a = \dfrac{v^2 - u^2}{2s}$

$a = \dfrac{(2.0\,\text{m s}^{-1})^2 - (0\,\text{m s}^{-1})^2}{2 \times 5.0\,\text{m}}$

$a = 0.4\,\text{m s}^{-2}$

Newton's second law:

$\Sigma F = ma$

$\Sigma F = 1.5 \times 10^3\,\text{kg} \times 0.4\,\text{m s}^{-2}$

$F(\text{by cable on load}) - w = 600\,\text{N}$

$F(\text{by cable on load}) = 600\,\text{N} + 1.5 \times 10^3\,\text{kg} \times 9.8\,\text{m s}^{-2}$

$F(\text{by cable on load}) = 1.53 \times 10^4\,\text{N}$

b $\Sigma F = ma$

$\Sigma F = 1.5 \times 10^3\,\text{kg} \times 0\,\text{m s}^{-2}$

$F(\text{by cable on load}) - w = 0\,\text{N}$

$F(\text{by cable on load}) = 1.5 \times 10^3\,\text{kg} \times 9.8\,\text{m s}^{-2}$

$F(\text{by cable on load}) = 1.47 \times 10^4\,\text{N}$

ANALYSING

9 a To stay together, each block must move with the same motion.

b $a = \dfrac{\Sigma F}{m}$

$a = \dfrac{20\,\text{N}}{2.0\,\text{kg} + 3.0\,\text{kg}}$

$a = 4.0\,\text{m s}^{-2}$

c i $\Sigma F = ma$

$F(\text{by A on B}) = m_B a_B$

$F(\text{by A on B}) = 3.0\,\text{kg} \times 4.0\,\text{m s}^{-2}$

$F(\text{by A on B}) = 12\,\text{N}$

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ii $\Sigma F = ma$

$20\text{ N} - F(\text{by B on A}) = m_A a_A$

$F(\text{by B on A}) = 20\text{ N} - 2.0\text{ kg} \times 4.0\text{ m s}^{-2}$

$F(\text{by B on A}) = 12\text{ N}$

This is the expected result from Newton's third law.

14.5 SECTION REVIEW

REMEMBERING

1 a Force acting for a time interval

b Product of mass and velocity

c Difference between two momenta

2 $\vec{F}\Delta t = \Delta\vec{p} = \Delta(m\vec{v})$

3 Impulse

4 In an isolated system, momentum is conserved throughout the time of any and all collisions.

UNDERSTANDING

5 The system must be isolated from any external impulses.

6 All impulses are equal and opposite; hence, all momentum changes are equal and opposite.

APPLYING

7 The forces on the receiver are equal in magnitude and opposite in direction to the forces on the agent (Newton's third law). All forces act over the same time interval; hence, all impulses are equal and opposite.

8 a Area under *F*-*t* graph

b Area under *F*-*t* graph

ANALYSING

9 $P_T(\text{before}) = P_T(\text{after})$

$p_{Ai} + p_{Bi} = p_{Af} + p_{Bf}$

$p_{Af} - p_{Ai} = p_{Bi} - p_{Bf}$

$p_{Af} - p_{Ai} = {}^{-}(p_{Bf} - p_{Bi})$

${}^{+}\Delta p_A = {}^{-}\Delta p_B$

14.6 SECTION REVIEW

REMEMBERING

1 See pages 309–10

UNDERSTANDING

2 a Visualisation makes the situation more real and enables all data to be related to real objects.

b All unknowns can be related algebraically across the entire collision.

3 Newton's third law states that for every action there is an equal and opposite reaction. Throughout a collision, actions always equal reactions. These take place over the same time interval to produce impulse, hence change in momentum.

APPLYING

4 a Take positive as being towards barrier:

$\Delta p = m\Delta v$

$\Delta p = 1.0 \times 10^3\text{ kg} \times (0\text{ m s}^{-1} - 20\text{ m s}^{-1})$

$\Delta p = -2.0 \times 10^4\text{ kg m s}^{-1}$

b $J(\text{by barrier on car}) = \Delta p$

$J = -2.0 \times 10^4\text{ kg m s}^{-1}$

c $F(\text{by barrier on car})\Delta t = \Delta p$

$F(\text{by barrier on car}) = \dfrac{\Delta p}{\Delta t}$

$F(\text{by barrier on car}) = \dfrac{-2.0 \times 10^4\text{ kg m s}^{-1}}{2.0\ s}$

$F(\text{by barrier on car}) = -1.0 \times 10^4\text{ N}$

By Newton's third law:

$F(\text{by barrier on car}) = F(\text{by car on barrier})$

$F(\text{by car on barrier}) = 1.0 \times 10^4\text{ N}$

5 a The unrestrained dog continues on in its state of uniform motion at 100 km h^{-1} (Newton's first law) until it hits the windscreen. The dog applies a force on the windscreen, which returns the favour (Newton's third law). The force by the windscreen on the dog causes the dog to decelerate (Newton's second law: $a = \dfrac{F}{m}$)

b $F(\text{by windscreen on dog})\Delta t = m\Delta v$

$F(\text{by windscreen on dog}) = \dfrac{m\Delta v}{\Delta t}$

$F(\text{by windscreen on dog}) = \dfrac{3.4\text{ kg} \times (0\text{ m s}^{-1} - 27.78\text{ m s}^{-1})}{0.150\text{ s}}$

$F(\text{by windscreen on dog}) = -630\text{ N}$

6 $P_{(\text{T before})} = P_{(\text{T after})}$

$50\text{ kg} \times 3.0\text{ m s}^{-1} + 80\text{ kg} \times 0\text{ m s}^{-1} = (50\text{ kg} + 80\text{ kg}) \times v_f$

$v_f = \dfrac{150\text{ kg m s}^{-1}}{130\text{ kg}}$

$v_f = 1.2\text{ m s}^{-1}$

ANALYSING

7 $p_{Pi} = m \times 1.5\text{ m s}^{-1}$

$p_{Pf} = m \times {}^{-}0.5\text{ m s}^{-1}$

$p_{Pf} - p_{Pi} = m \times {}^{-}0.5\text{ m s}^{-1} - m \times 0.5\text{ m s}^{-1}$

$p_{Pf} - p_{Pi} = m \times {}^{-}2.0\text{ m s}^{-1}$ (1)

$p_{Qi} = m \times {}^{-}1.5\text{ m s}^{-1}$

$p_{Qf} = m \times 0.5\text{ m s}^{-1}$

$p_{Qf} - p_{Qi} = m \times 0.5\text{ m s}^{-1} - m \times {}^{-}1.5\text{ m s}^{-1}$

$p_{Qf} - p_{Qi} = m \times 2.0\text{ m s}^{-1}$ (2)

Insert equation (1) into equation (2):

$(p_{Pf} - p_{Pi}) + (p_{Qf} - p_{Qi}) = m \times {}^{-}2.0\text{ m s}^{-1} + m \times 2.0\text{ m s}^{-1}$

$(p_{Pf} - p_{Pi}) + (p_{Qf} - p_{Qi}) = 0$

8 $p_{Ti} = {}^{-}66.0\ \text{kg m s}^{-1}$

Initial momentum:

$p_{Tf} = p_{Kf} + p_{Lf}$

$p_{Tf} = 6.0\ \text{kg} \times {}^{-}10\ \text{m s}^{-1} + 12.0\ \text{kg} \times 0.5\ \text{m s}^{-1}$

$p_{Tf} = {}^{-}54.0\ \text{kg m s}^{-1}$

Initial momentum ≠ Final momentum

This is not possible.

9 Take positive to be in direction of rebound velocity:

a $J = \text{area} \times F - t$ graph

$J = \frac{1}{2} \times 200\ \text{N} \times 0.030\ \text{s}$

$J = 3.0\ \text{N s}$

b $J = \Delta p$

$0.058\ \text{kg} \times (v_f - {}^{-}30\ \text{m s}^{-1}) = 3.0\ \text{N s}$

c $v_f + 30\ \text{m s}^{-1} = \frac{3.0\ \text{N s}}{0.058\ \text{kg}}$

$v_f = 21.7\ \text{m s}^{-1}$

CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 Agent/receiver focuses attention on the external action of one object on another.

2 Consider: net force and forces on materials that stretch, compress or tear.

3 Responses will vary.

CATEGORY QUESTIONS

4 Qualitative vs quantitative

5 Force results in an acceleration of a given mass, measured in Newton; impulse is a measure of change in momentum, measured in kg m s^{-1}; momentum is the product of mass and velocity, measured in kg m s^{-1}.

6 a A collision is an event where two or more bodies exert forces on each other over a period of time. The forces may be contact or non-contact in their nature.

b i Billiard ball collisions; explosions

ii Electrostatic repulsion; planetary gravitational slingshot manoeuvres

ELABORATION QUESTIONS

7 Consider agent/receiver and net force

8 Newton's first law

EVIDENCE QUESTIONS

9 Newton's third law criteria

10 a i Calculating impulse is more difficult

ii A fair test of restraint

b Consider initial and final speeds

c Use road trauma research (e.g. from CARRS-Q, MUARC, ANCAP)

END-OF-CHAPTER EXAM

1 C

2 C

3 A

4 D

5 C

6 A

7 a external

b moment

8 Newton's second law states that: $a = \frac{\Sigma F}{m}$; weight force downwards and any upwards air resistance are the forces applied to the ball. The ball accelerates at $9.8\ \text{m s}^{-2}$ when other forces are negligible.

9 Area under F-t graph; area under a-t, multiplied by mass.

10 Equal magnitude; opposite direction; same type; act on different objects

11 Mass: amount of matter; weight: gravitational force applied to mass

12 $a = \frac{\Sigma F}{m}$

$m = \frac{\Sigma F}{a}$

$m = \frac{200\ \text{N} - 20\ \text{N}}{4\ \text{m s}^{-2}}$

$m = 45\ \text{kg}$

13 $\Sigma F = ma$

$a = \frac{\Delta v}{\Delta t}$

$a = \frac{12\ \text{m s}^{-1} - 0\ \text{m s}^{-1}}{2\ \text{s}}$

$a = 10\ \text{m s}^{-2}$

$\Sigma F = 80\ \text{kg} \times 10\ \text{m s}^{-2}$

$\Sigma F = 800\ \text{N}$

14 $\frac{\Sigma F(\text{aeroplane})}{\Sigma F(\text{car})} = \frac{\{ma\}_{\text{aeroplane}}}{\{ma\}_{\text{car}}}$

but, $a_{\text{aeroplane}} = a_{\text{car}}$

$\frac{\Sigma F(\text{aeroplane})}{\Sigma F(\text{car})} = \frac{m_{\text{aeroplane}}}{m_{\text{car}}}$

$\frac{\Sigma F(\text{aeroplane})}{\Sigma F(\text{car})} = \frac{2.0 \times 10^5\ \text{kg}}{1.0 \times 10^3\ \text{kg}}$

$\frac{\Sigma F(\text{aeroplane})}{\Sigma F(\text{car})} = 2.0 \times 10^2$

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15 For the combination of masses, hence each mass separately:

$$a = \frac{\Sigma F}{m}$$

$$a = \frac{168\,\text{N}}{6\,\text{kg} + 12\,\text{kg} + 3\,\text{kg}}$$

$$a = 8.0\,\text{m}\,\text{s}^{-2}$$

For 12 kg mass B:

$$\Sigma F = ma$$

$$F(\text{by A on B}) - F(\text{by C on B}) = 12\,\text{kg} \times 8.0\,\text{m}\,\text{s}^{-2}$$

$$F(\text{by A on B}) - F(\text{by C on B}) = 96\,\text{N} \quad (1)$$

By Newton's third law:

$$F(\text{by C on B}) = F(\text{by B on C}) = m_C a_C$$

$$F(\text{by C on B}) = 3.0\,\text{kg} \times 8.0\,\text{m}\,\text{s}^{-2}$$

$$F(\text{by C on B}) = 24\,\text{N} \quad (2)$$

Substitute equation (2) into equation (1)

$$F(\text{by A on B}) - 24\,\text{N} = 96\,\text{N}$$

$$F(\text{by A on B}) = 120\,\text{N}$$

16 Impulse = change in momentum:

a $F(\text{by bat on ball})\Delta t = (\Delta p)_{\text{ball}}$

$$F(\text{by bat on ball})\Delta t = m_{\text{ball}}\Delta v_{\text{ball}}$$

$$F(\text{by bat on ball}) = \frac{m_{\text{ball}}\Delta v_{\text{ball}}}{\Delta t}$$

Take the return direction to be positive:

$$F(\text{by bat on ball}) = \frac{0.15\,\text{kg} \times \left(38\,\text{m}\,\text{s}^{-1} - {}^{-}32\,\text{m}\,\text{s}^{-1}\right)}{0.75 \times 10^{-3}\,\text{s}}$$

$$F(\text{by bat on ball}) = 1.4 \times 10^{4}\,\text{N}$$

b By Newton's third law:

$$F(\text{by bat on ball}) = F(\text{by ball on bat})$$

$$F(\text{by ball on bat}) = 1.4 \times 10^{4}\,\text{N}$$

17 $\vec{J}$ = area under F-t graph

$$\vec{J} = \frac{1}{2} \times 1.0 \times 10^{3}\,\text{N} \times 24 \times 10^{-3}\,\text{s}$$

$$\vec{J} = 12\,\text{N}\,\text{s}$$

$$m\Delta v = 12\,\text{N}\,\text{s}$$

$$0.15\,\text{kg} \times \left(v_f - {}^{-}35\,\text{m}\,\text{s}^{-1}\right) = 12\,\text{N}\,\text{s}$$

$$v_f = 45\,\text{m}\,\text{s}^{-1}$$

Impulse = momentum change

Take positive to be the outward direction.

18 Gravitational force on the Moon is less than on Earth. Scales calibrated on Earth will read approximately one-sixth of Earth measure.

19 Unrestrained occupants continue on at the speed immediately before the crash (Newton's first law).

20 Impulse = momentum change. For a given collision, the impulse and hence momentum change is the same. Crumple zones increase the time for the crash, so the force is reduced.

Seatbelts enable the occupant to remain in the vehicle and to slow with the vehicle.

CHAPTER 15: NEWTON'S LAWS OF MOTION

15.1 SECTION REVIEW

REMEMBERING

1 Fundamental quantity that can be transferred and transformed; difference in energy relative to a defined zero; energy associated with movement; energy ready to be transformed; energy stored in a system and able to be completely returned in a different form; energy stored in a gravitational field

2 In a closed system, no energy can come into the system, no energy can leave the system and no energy can be created or destroyed within the system

UNDERSTANDING

3 An isolated system is not able to receive energy from or transfer energy to another system.

4 a Work done on or by a system is the same as the energy change to or by the system: $\Delta W = \Delta E$

b Work, $W = \Delta E = F_{\parallel}\Delta s$; $F_{\parallel}$ = component of force parallel to the direction of movement; s = displacement; ΔE = energy transferred

5 Energy is neither created nor destroyed; it is merely transformed. It is measured relative to a defined starting value or point. Measures are only made relative to such a given point.

6 Potential energy is stored in a spring when the spring is changed in length; gravitational potential energy is stored in the gravitational field according to the position of a mass in the field.

APPLYING

7 a $E_k = \frac{1}{2}mv^2$

$$E_k = \frac{1}{2} \times 3.0\,\text{kg} \times \left(8.0\,\text{m}\,\text{s}^{-1}\right)^2$$

$$E_k = 96\,\text{J}$$

b $60\,\text{km}\,\text{h}^{-1} = \frac{60\,\text{km}\,\text{h}^{-1} \times 10^{3}\,\text{m}\,\text{km}^{-1}}{3600\,\text{s}\,\text{h}^{-1}} = 16.7\,\text{m}\,\text{s}^{-1}$

$$E_k = \frac{1}{2}mv^2$$

$$E_k = \frac{1}{2} \times 3.0\,\text{kg} \times \left(16.67\,\text{m}\,\text{s}^{-1}\right)^2$$

$$E_k = 417\,\text{J}$$

8 a $W = \Delta E_k = F_{\parallel}\Delta s$

$$\Delta E_k = 20\,\text{N} \times 5.0\,\text{m}$$

$$\Delta E_k = 100\,\text{J}$$

b $\Delta E_k = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2$

$\frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2 = 100\,\text{J}$

$v_f^2 - v_i^2 = 2 \times \frac{100\,\text{J}}{8.0\,\text{kg}}$

$v_f^2 - \left(10\,\text{m s}^{-1}\right)^2 = 25\,\text{J kg}^{-1}$

$v_f = 11.2\,\text{m s}^{-1}$

ANALYSING

9 a Curved path; if the speed is constant, the object describes a circle

b The force is always at right angles so there is no component of force parallel to the path (tangent) to do work.

REFLECTING

10 Answers will vary

15.2 SECTION REVIEW

REMEMBERING

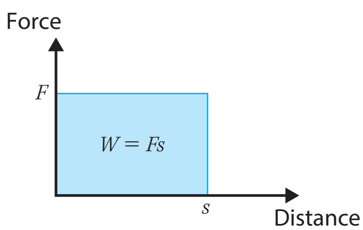
1 Work is the force applied to move an object over a distance in the direction of the force: $W = F_{\parallel}\Delta s$

2 Work is the effort required to transfer energy; $\Delta W = \Delta E$

3 Work done = area under a force–distance graph

UNDERSTANDING

4



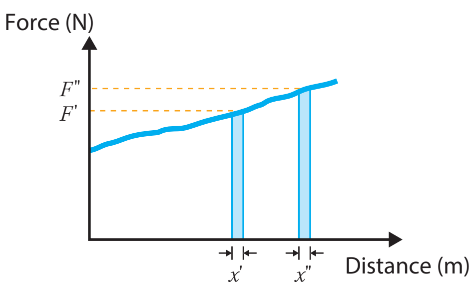
5 a $F(\text{by spring}) = k(^{-}x)$

b $F(\text{by spring})$ = force applied by spring

x = change of length of spring

k = stiffness

c



APPLYING

6 $W = F\Delta s$

$W = 1.5 \times 10^5\,\text{N} \times 5.0 \times 10^{-2}\,\text{m}$

$W = 7.5 \times 10^3\,\text{N}$

7 $W = F_{\parallel}s$

$W = 30\,\text{N} \times \cos 30° \times 20\,\text{m}$

$W = 519.6\,\text{J}$

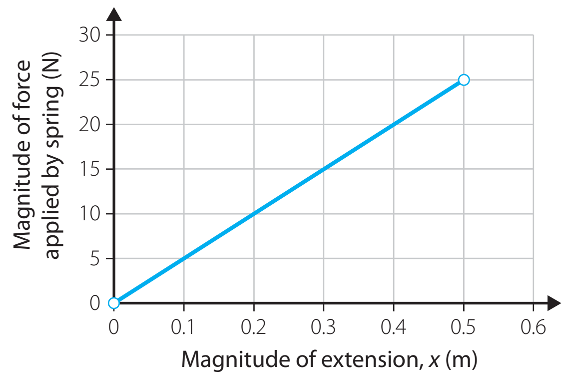
8 $W = F_{\parallel}s$

$W = 400\,\text{N} \times 9.0\,\text{m} + \left(400\,\text{N} + 200\,\text{N}\right) \times 6.0\,\text{m}$

$W = 7.2 \times 10^3\,\text{N}$

ANALYSING

9 a



b $E = \frac{1}{2}kx^2$

$x = 50\,\text{cm} - 30\,\text{cm} = 20\,\text{cm}$

$E = \frac{1}{2} \times 50\,\text{N m}^{-1} \times \left(0.20\,\text{m}\right)^2$

$E = 1.0\,\text{J}$

15.3 SECTION REVIEW

REMEMBERING

1 $\Delta E_T = \Delta E_K + \Delta E_P = 0$

2 a $\Delta W = mg\Delta h\ (\Delta h > 0; h_2 > h_1)$

b $\Delta W = mg\Delta h\ (\Delta h < 0; h_2 < h_1)$

3 a $\frac{1}{2}mv_i^2 = mgH$

b $v_i = \sqrt{2gH}$

c $H = \frac{v_i^2}{2gH}$

UNDERSTANDING

4 For objects going up, the distance above the surface is positive as the potential energy stored in the system increases.

5 Work is done only when there is a component of the force in the direction of the field. 'Near Earth', horizontal motion is at right angles to Earth's gravitational field.

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APPLYING

6 a $\Delta E_p = mg\Delta h$

$\Delta E_p = 0.160\,\text{kg} \times 9.8\,\text{m s}^{-2} \times 20.0\,\text{m}$

$\Delta E_p = 31.4\,\text{N}$

b $v_i = \sqrt{2gH}$

$v_i = \sqrt{2 \times 9.8\,\text{m s}^{-2} \times 20.0\,\text{m}}$

$v_i = 19.8\,\text{m s}^{-1}$

7

		E_P (J)	E_K (J)	E_T (J)
a	Top	$E_P = mgh$ $E_P = 50\,\text{kg} \times 9.8\,\text{m s}^{-2} \times 20.0\,\text{m}$ $E_P = 9.8 \times 10^3$ J	0	9.8×10^3 J
b	Middle	4.9×10^3 J	4.9×10^3 J	9.8×10^3 J
c	Bottom	0	9.8×10^3 J	9.8×10^3 J

ANALYSING

8 If $E_P = 0$ J when $h = 0$ m then ΔE_P (at H) $= mgH - 0\,\text{J} = mgH$
If $E_P = 100$ J when $h = 0$ then
ΔE_P (at H) $= (100\,\text{J} + mgH) - 100\,\text{J} = mgH$

15.4 SECTION REVIEW

REMEMBERING

1 See page 335.

UNDERSTANDING

2 A line can be approximated by a series of very small steps. The area under each step is a {force × distance} rectangle with units of joule; hence, it is work. The sum of all the very thin rectangles adds up to the area under the graph, and hence is the total work done.

3 $W = \frac{1}{2} \times x \times ks$

$W = \frac{1}{2} kx^2$

APPLYING

4 a $W = F_{\|} s$

$W = 250\,\text{N} \times (10\,\text{m} - 0\,\text{m})$

$W = 2.5 \times 10^3\,\text{N}$

b $W = F_{\|} s$

$W = 250\,\text{N} \times (17\,\text{m} - 3\,\text{m})$

$W = 3.5 \times 10^3\,\text{N}$

5 a i $W(\text{by A}) = F(\text{by A})s$

$\Sigma F = F(\text{by A}) - f$

$F(\text{by A}) = \Sigma F + f$

$F(\text{by A}) = 30\,\text{N} + 28\,\text{N}$

$F(\text{by A}) = 58\,\text{N}$

$W(\text{by A}) = 58\,\text{N} \times 4.0\,\text{m}$

$W(\text{by A}) = 232\,\text{J}$

ii $W(\text{by A}) = F(\text{by A})s$

$W(\text{by A}) = 58\,\text{N} \times 16\,\text{m}$

$W(\text{by A}) = 928\,\text{J}$

b i $W(\text{by B}) = F(\text{by B})s$

$\Sigma F = F(\text{by B}) + F(\text{by A}) - f$

$F(\text{by B}) = \Sigma F - F(\text{by A}) + f$

$F(\text{by B}) = 75\,\text{N} - 58\,\text{N} + 28\,\text{N}$

$F(\text{by B}) = 45\,\text{N}$

$W(\text{by B}) = 45\,\text{N} \times (12\,\text{m} - 8.0\,\text{m})$

$W(\text{by B}) = 180\,\text{J}$

ii $W(\text{by B}) = F(\text{by B})s$

$W(\text{by B}) = 45\,\text{N} \times (20\,\text{m} - 8.0\,\text{m})$

$W(\text{by B}) = 540\,\text{J}$

c $W(\text{by friction}) = F(\text{by friction})s$

$W(\text{by friction}) = 28\,\text{N} \times 24\,\text{m}$

$W(\text{by friction}) = 672\,\text{J}$

6 a $W(\text{by train}) = F(\text{by train})s$

$\Sigma F = F(\text{by train}) - f$

$F(\text{by train}) = \Sigma F + f$

$\Sigma F = ma$

$a = \text{gradient}_{\text{v-t graph}} = \frac{\Delta v}{\Delta t}$

$a = \frac{10\,\text{m s}^{-1} - 0\,\text{m s}^{-1}}{600\,\text{s} - 0\,\text{s}} = \frac{1}{60}\,\text{m s}^{-2}$

$\Sigma F = 5.5 \times 10^6\,\text{kg} \times \frac{1}{60}\,\text{m s}^{-2}$

$\Sigma F = 9.2 \times 10^4\,\text{N}$

$s = \text{area under}_{\text{v-t graph}}$

$s = \frac{1}{2} \times 10\,\text{m s}^{-1} \times 600\,\text{s}$

$s = 3.0 \times 10^3\,\text{m}$

$F(\text{by train}) = 9.2 \times 10^4\,\text{N} + 1.0 \times 10^4\,\text{N}$

$F(\text{by train}) = 1.02 \times 10^5\,\text{N}$

$W(\text{by train}) = 1.02 \times 10^5\,\text{N} \times 3.0 \times 10^3$

$W(\text{by train}) = 3.1 \times 10^8\,\text{J}$

b $W(\text{by train}) = F(\text{by train})x$

$\Sigma F = F(\text{by train}) - f$

$F(\text{by train}) = \Sigma F + f$

$F(\text{by train}) = 0\ \text{N} + 1.0 \times 10^4\ \text{N}$

$x = \text{area under}_{v-t\ \text{graph}}$

$x = 10\ \text{m s}^{-1} \times (1800\ \text{s} - 1200\ \text{s})$

$x = 6.0 \times 10^3\ \text{m}$

$W(\text{by train}) = 1.0 \times 10^4\ \text{N} \times 6.0 \times 10^3\ \text{m}$

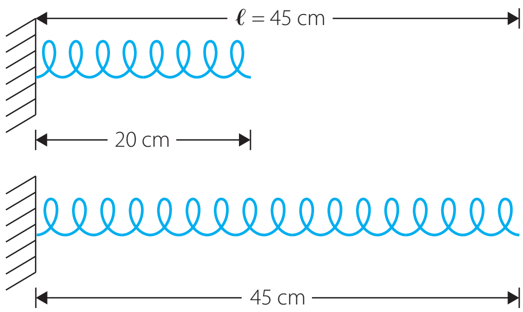
$W(\text{by train}) = 6.0 \times 10^7\ \text{J}$

ANALYSING

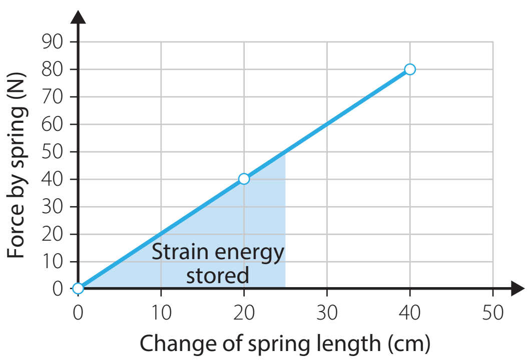
7 $F(\text{by spring}) = k(L - \ell),\ L < \ell$

$F(\text{by spring}) = k(\ell - L),\ \ell < L$

8 a



b



c See graph in part b

d $\frac{1}{2}mv^2 = \frac{1}{2}kx^2$

$v = \sqrt{\frac{k}{m}x^2}$

$v = \sqrt{\frac{200\,\text{N m}^{-1}}{0.200\,\text{kg}} \times (0.45\,\text{m} - 0.20\,\text{m})^2}$

$v = 7.91\,\text{m s}^{-1}$

15.5 SECTION REVIEW

REMEMBERING

1 a Momentum is conserved throughout; the kinetic energy at the start is the same as the kinetic energy at the end

b Momentum is conserved throughout; the kinetic energy at the start is different from the kinetic energy at the end

2 a Momentum

b Kinetic energy

UNDERSTANDING

3 a impulse–momentum

b work–energy

4 Both momentum and kinetic energy at the start of a collision are conserved in elastic collisions

APPLYING

5 a Take right to be positive:

$P_{\text{T, initial}} = P_{\text{T, final}}$

$(m_P v_P)_i + (m_Q v_Q)_i = (m_P v_P)_f + (m_Q v_Q)_f$

$(4.0\ \text{kg} \times 3.0\ \text{m s}^{-1})_i + (5.0\ \text{kg} \times -2.0\ \text{m s}^{-1})_i$

$= (4.0\ \text{kg} \times -1.0\ \text{m s}^{-1})_f + (5.0\ \text{kg} \times v_Q)_f$

$2.0\ \text{kg m s}^{-1} = (5.0\ \text{kg} \times v_Q)_f - 4.0\ \text{kg m s}^{-1}$

$v_{Q,f} = \frac{6.0\ \text{kg m s}^{-1}}{5.0\ \text{kg}}$

$v_{Q,f} = 1.2\ \text{m s}^{-1}$

b $F(\text{by P on Q})\Delta t = (\Delta p)_Q$

$F(\text{by P on Q}) = \frac{(m_Q v_Q)_f - (m_Q v_Q)_i}{\Delta t}$

$F(\text{by P on Q}) = \frac{(5.0\ \text{kg} \times 1.2\ \text{m s}^{-1})_f - (5.0\ \text{kg} \times -2.0\ \text{m s}^{-1})_i}{0.4\ \text{s}}$

$F(\text{by P on Q}) = 40\ \text{N}$

c Compare initial and final kinetic energies:

$E_{K,i} = \left(\frac{1}{2}m_P v_P^2\right)_i + \left(\frac{1}{2}m_Q v_Q^2\right)_i$

$E_{K,i} = \left[\frac{1}{2} \times 4.0\ \text{kg} \times (3.0\ \text{m s}^{-1})^2\right]_i + \left[\frac{1}{2} \times 5.0\ \text{kg} \times (-2.0\ \text{m s}^{-1})^2\right]_i$

$E_{K,i} = 28\ \text{J}$

$E_{K,f} = \left(\frac{1}{2}m_P v_P^2\right)_f + \left(\frac{1}{2}m_Q v_Q^2\right)_f$

$E_{K,f} = \left[\frac{1}{2} \times 4.0\ \text{kg} \times (-1.0\ \text{m s}^{-1})^2\right]_f + \left[\frac{1}{2} \times 5.0\ \text{kg} \times (1.2\ \text{m s}^{-1})^2\right]_f$

$E_{K,f} = 5.6\ \text{J}$

$E_{K,i} \neq E_{K,f}$

The collision is inelastic.

6 a $F(\text{by seatbelt on person})\Delta x = \Delta E_{\text{K, person}}$

$F(\text{by seatbelt on person}) = \frac{\Delta E_{\text{K, person}}}{\Delta x}$

$F(\text{by seatbelt on person}) = \frac{\left(\frac{1}{2}m_P v_P^2\right)_f - \left(\frac{1}{2}m_P v_P^2\right)_i}{\Delta x}$

$F(\text{by seatbelt on person}) =$

$\frac{\left[\frac{1}{2} \times 100.0\ \text{kg} \times (0\ \text{m s}^{-1})^2\right] - \left[\frac{1}{2} \times 100.0\ \text{kg} \times (10\ \text{m s}^{-1})^2\right]_i}{1.0\ \text{m}}$

$F(\text{by seatbelt on person}) = 5.0 \times 10^3\ \text{N}$

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b $F(\text{by seatbelt on person})\Delta t = \Delta p_{\text{person}}$

$$\Delta t = \frac{(m_P v_P)_f - (m_P v_P)_i}{F(\text{by seatbelt on person})}$$

$$\Delta t = \frac{(100\ \text{kg} \times 0\ \text{m s}^{-1}) - (100\ \text{kg} \times -10\,\text{m s}^{-1})}{5.0 \times 10^3\ \text{N}}$$

$$\Delta t = 0.20\ \text{s}$$

ANALYSING

7 if $\Delta h_f = \Delta h_i$, $v_f = v_i$ and $v_f^2 = v_i^2$
$\Delta P = 0$ and $\Delta E_K = 0$

CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 Work causes energy to be transferred or transformed

2 $W = F_{||}s = Fs\cos\theta$

3 a Area under g vs h graph multiplied by mass

b Area under F(by spring) vs extension

4 F = magnitude of force applied by spring; x = magnitude of change in length of spring

CATEGORY QUESTIONS

5 Isolated system.

6 $\vec{J} = \vec{F}\Delta t$; $\vec{p} = m\vec{v}$; $E_K = \frac{1}{2}mv^2$

a i $\Delta P_T = 0$

ii $\Delta E_K = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2$

b Compare initial and final totals for kinetic energy.

7 In elastic collisions both momentum and energy are conserved. In inelastic collisions momentum is conserved; however, energy is 'lost' to other forms. Examples of elastic collisions include potential energy return to kinetic energy, movement in gravitational field, (perfect) springs and billiard balls colliding. Examples of inelastic collisions are a car crashing into a tree and sticky collisions.

8 Momentum is conserved.

ELABORATION QUESTIONS

9 When kinetic energy is equated to gravitational potential energy in a gravitational field, the equations are simplified to the equation $v_{max} = \sqrt{2gh_{max}}$.

10 Movement with components in the direction of the gravitational field only affects work, hence energy transfers.

EVIDENCE QUESTIONS

11 Impulse is the measure of the change of momentum; that is, mass by change in velocity. Work is the measure of the change in energy. They do not represent the same values.

12 a Same masses at same initial and final speeds

b Use road trauma research (e.g. from CARRS-Q, MUARC, ANCAP)

END-OF-CHAPTER EXAM

1 C

2 A

3 C

4 C

5 A

6 Isolated system; no energy in; no energy out; no energy created inside system

7 a $W(\text{by net force}) = \Sigma F \times s$

$W = 200\ \text{N} \times 12\ \text{m}$

$W = 2.4\ \text{kJ}$

b $W(\text{by winch}) = F(\text{by winch})s$

$\Sigma F = F(\text{by winch}) - f$

$F(\text{by winch}) = \Sigma F + f$

$F(\text{by winch})x = \left(\Sigma F_{0-12\,\text{m}} + 30\,\text{N}\right) \times (12\ \text{m} - 0\ \text{m})$

$+\left(\Sigma F_{12-24\,\text{m}} + 30\,\text{N}\right) \times (36\,\text{m} - 12\ \text{m})$

$W(\text{by winch}) = 230\ \text{N} \times 12\ \text{m} + 530\,\text{N} \times 24\ \text{m}$

$W(\text{by winch}) = 15\ \text{kJ}$

8 a $\Delta E_p = mg\Delta h$

$\Delta E_p = 60\ \text{kg} \times 9.8\,\text{ms}^{-2} \times (1.8\,\text{m} - 0.63\,\text{m})$

$\Delta E_p = 688\ \text{J}$

b $v = \sqrt{2gh}$

$v = \sqrt{2 \times 9.8\ \text{ms}^{-2} \times (1.8\ \text{m} - 0.63\ \text{m})}$

$v = 4.8\ \text{ms}^{-1}$

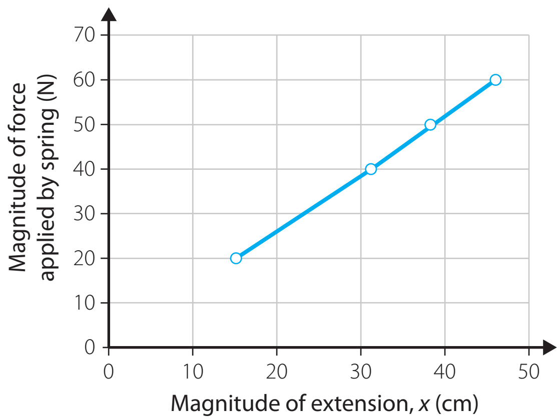
c $\Delta E_p = mg\Delta h$

$\Delta E_p = 60\,\text{kg} \times 9.8\,\text{ms}^{-2} \times (1.8\,\text{m} - 0.42\,\text{m})$

$\Delta E_p = 753\ \text{J}$

$\Delta E_k = 753\ \text{J}$

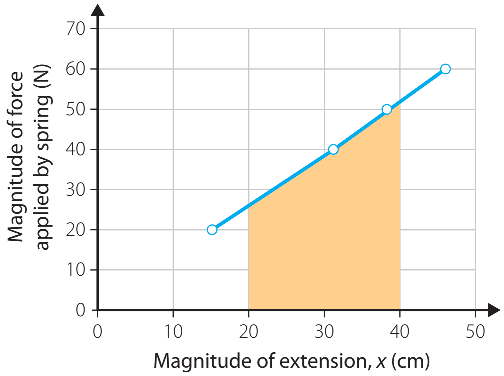
9 a



b $k = \dfrac{60\ \text{N} - 20\,\text{N}}{0.46\ \text{m} - 0.15\ \text{m}}$

$k = 129.03\ \text{N m}^{-1}$

c



d $E_{\text{p, spring}} = \frac{1}{2}kx^2$

$E_{\text{p, spring}} = \frac{1}{2} \times 133 \text{ N m}^{-1} \times \left[(0.40 \text{ m})^2 - (0.20 \text{ m})^2\right]$

$E_{\text{p, spring}} = 7.74 \text{ J}$

10 a $W = F\Delta s = \Delta E_k$

$F = \frac{\Delta E_k}{\Delta x}$

$F = \frac{\frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2}{\Delta x}$

$F = \frac{\frac{1}{2} \times 8.0 \text{ kg} \times \left[(0 \text{ m s}^{-1})^2 - (20 \text{ m s}^{-1})^2\right]}{0.05 \text{ m}}$

$F = 3.2 \times 10^4 \text{ N}$

b $J = F\Delta t = m\Delta v$

$\Delta t = \frac{m\Delta v}{F}$

$\Delta t = \frac{8.0 \text{ kg} \times (0 \text{ m s}^{-1} - 20 \text{ m s}^{-1})}{-3.2 \times 10^4 \text{ N}}$

$\Delta t = 5.0 \times 10^{-3} \text{ s}$

11 Seatbelts keep the occupants in place, so they slow with the vehicle. Crumple zones slow the vehicle over longer times and distances than vehicles with no crumple zones. If momentum transfers, hence impulses, are the same for both types of vehicle, then the force by the vehicle is reduced as the time to come to a stop is increased. Similarly, if energy transfers, hence work done on occupants, are the same for both types of vehicle, then the force by the vehicle is reduced as the distance to come to a stop is increased.

12 Newton's third law states that for every action there is an equal and opposite reaction. Throughout a collision, objects experience forces, moment by moment; hence, moment by moment there is an action–reaction pair operating. These two forces act over the same time intervals. Thus, the impulse by A on B must be the same as the impulse by B on A. For energy transfers, work done may be converted to potential energy in the system. This causes the kinetic energy to be decreased during the collision. If all the potential energy is returned by the end of the collision, the collision is elastic; otherwise, it is inelastic.

CHAPTER 16: WAVE PROPERTIES

16.1 SECTION REVIEW

REMEMBERING

1 All waves transfer energy from one place to another.

2 The intensity of a wave is a measure of the energy per unit time travelling through a unit area perpendicular to the direction of travel.

UNDERSTANDING

3 Since the intensity of a wave is inversely proportional to the distance from the source squared, a doubling of the distance results in the intensity becoming one quarter as strong.

ANALYSING

4 The energy of the stone dropped into a pond does spread as a sphere, however the interface upon which we view these waves is a slice through the mid-point and as such appears as a circle. The energy that is travelling under the water and through the air is invisible to us.

16.2 SECTION REVIEW

REMEMBERING

1 A mechanical wave is a wave that requires a physical substance to be able to propagate.

2 A wavefront is an imaginary surface joining all points in space reached at the same instant by a wave propagating through a medium.

3 The medium is the substance whose particles oscillate in response to the energy of a wave travelling through it.

UNDERSTANDING

4 Mechanical waves travel in a medium made of interconnected particles that are progressively disturbed and oscillate about their mean position due to the motion of the energy through them.

5 The ocean waves shown in Figure 16.2.1 are representative of plane wavefronts as the rays that can be drawn perpendicularly to them are parallel to each other.

16.3 SECTION REVIEW

REMEMBERING

1 a A pulse is a single wavefront travelling through a medium.

b A continuous wave is a repeating wave passing through a medium.

c A compression is a region of high pressure in a mechanical wave.

d A rarefaction is a region of lower pressure in a mechanical wave.

UNDERSTANDING

2 In a transverse wave, the particles of the medium are oscillating in a direction perpendicular to the direction of

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wave motion, whereas in a longitudinal wave, the particles of the medium are oscillating in a direction parallel to the direction of wave motion.

3 A single disturbance at the end of a string will produce a single pulse, whereas a continuous up and down disturbance will create a continuous wave.

16.4 SECTION REVIEW

REMEMBERING

1 a Longitudinal
  b Transverse
  c Longitudinal
  d Transverse
  e Transverse

2 a A compression is a region of high pressure in a mechanical wave.
  b A rarefaction is a region of lower pressure in a mechanical wave.

UNDERSTANDING

3 A disturbance on a string will result in a portion of the string being displaced in a direction transverse to the string itself. The displacement of these particles will apply a force on their adjacent particles.

4 In a water wave, the particles of water oscillate in a circular pattern below the surface; however on the surface they are seen to be displaced in a direction transverse to the direction of travel by the wave.

5 In a sound wave, the particles of the medium oscillate parallel to the direction of travel forming localised high-pressure compressions and low-pressure rarefactions. This pressure differential applies a force on other particles in the medium.

6 Seismic earthquake waves travel through the medium of Earth. The faster P waves are longitudinal compression waves whereas the slower S waves travel as transverse waves.

ANALYSE

7 Answers will vary but should include:
- a tear in the eardrum preventing the incoming sound waves from sending vibrations onto the small bones of the ear
- a break in one of the small bones failing to allow the vibration to pass through the ear
- the hairs of the inner ear failing to transmit electrical impulses to the nervous system.

8 Answers will vary but should include:
- discussion regarding the different speed of travel of the S and P waves in different media
- this resulting in a difference in the time delay between the arrival of the P and S waves at a measuring point depending on the density of the medium.

16.5 SECTION REVIEW

REMEMBERING

1 a A crest is the positive peak of a wave
  b A trough is the negative peak of a wave
  c The displacement of a particle in a medium is the straight-line distance between the current position of a particle in a wave and its mean position.
  d The amplitude of a wave is the maximum displacement of a particle in a wave from its mean position.
  e The period of a wave is the time it takes before a wave repeats itself.
  f The frequency of a wave is the number of whole waves of cycles in one second.
  g The wavelength of a wave is the distance travelled by a wave before it repeats itself.
  h The wave velocity is the velocity at which crests move through a medium.

2 A displacement–time graph can give information about the amplitude and period of a wave

3 A displacement–distance graph can give information about the amplitude and wavelength of a wave.

4 The properties of the medium through which a wave is travelling has the greatest impact on the velocity of the wave.

UNDERSTANDING

5 In this section, displacement refers to the straight-line distance that a particle of the medium through which a wave is passing is displaced from its mean position, whereas the distance is the position of a particle along the axis of wave travel.

APPLYING

6 $f = \frac{1}{T}$

Apply the frequency equation

$T = \frac{1}{f}$

Rearrange the equation to make the required T the subject

$T = \frac{1}{23\,\text{Hz}}$

Insert known values

$T = 0.043\,478\,\text{s}$

Calculate the answer

$T = 4.3 \times 10^{-2}\,\text{s}$

Give the answer to the correct number of significant figures

7 a $v = \frac{\lambda}{T}$

Apply the wave velocity formula

$v = \frac{0.6\,\text{m}}{0.5\,\text{s}}$

Insert known values

$v = 1.2\,\text{m s}^{-1}$

Calculate the answer to the correct number of significant figures b $f = \dfrac{1}{T}$

Apply the frequency equation

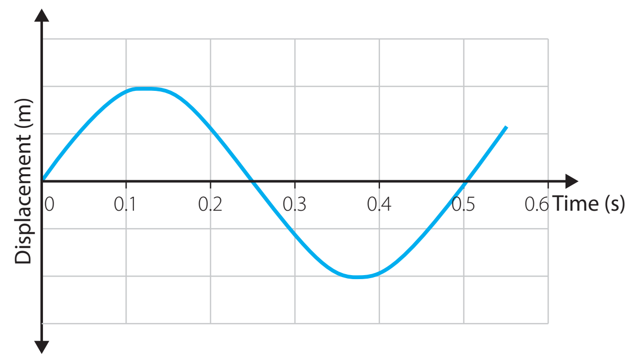
$f = \dfrac{1}{0.5\,\text{s}}$

Insert known values

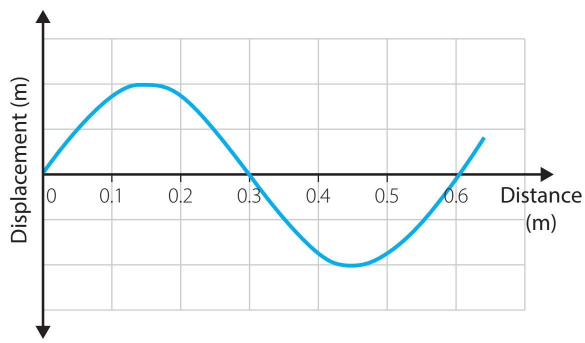
$f = 2.0\,\text{Hz}$

Calculate the answer to the correct number of significant figures

c



d



8 $v = \dfrac{\lambda}{T}$

Apply the velocity equation

$T = \dfrac{\lambda}{v}$

Rearrange the equation to make the required T the subject

$T = \dfrac{150\,\text{km}}{800\,\text{km}\,\text{h}^{-1}}$

Insert known values

$T = 0.1875\,\text{h}$

Calculate the answer

$T = 0.1875\,\text{h} \times \dfrac{3600\,\text{s}}{1\,\text{h}}$

Apply the conversion factor

$T = 675\,\text{s}$

Calculate the answer

$T = 700\,\text{s}$

Give the answer to the correct number of significant figures

9 a $A = 0.6\,\text{m}$ (from graph)

b $T = 0.125\,\text{s}$ (from graph)

c $f = \dfrac{1}{T}$

Apply the frequency equation

$f = \dfrac{1}{0.125\,\text{s}}$

Insert the known period

$f = 8\,\text{Hz}$

Calculate the answer

d $\lambda = 4\,\text{m}$

e $v = f\lambda$

Apply the wave velocity formula

$v = 8\,\text{Hz} \times 4\,\text{m}$

Insert known values

$v = 32\,\text{m}\,\text{s}^{-1}$

Calculate the answer

16.6 SECTION REVIEW

REMEMBERING

1 The reflection of a wave involves the change in direction of a wavefront at a boundary between two media so that the wavefront continues travelling in the first medium.

2 The wavefront is reflected in an inverted orientation relative to its orientation when it strikes the boundary.

3 The wavefront is reflected in an upright orientation relative to its orientation when it strikes the boundary.

4 When a wave pulse meets a junction with a string of higher density, part of the wave is reflected and part of the wave is transmitted into the new string. The reflected portion travels in an inverted orientation, with a decreased amplitude and an equal velocity relative to its behaviour when it meets the junction. The transmitted portion travels in an upright orientation, with a decreased amplitude and a lower velocity relative to its behaviour when it meets the junction.

5 When a wave is incident upon a surface, the angle of reflection is equal to the angle of incidence.

UNDERSTANDING

6 Both reverberation and echoes are caused by the reflection of sound waves at boundaries. A reverberation occurs when too many sound wave reflections arrive at your ear for you to be able to distinguish between them, while an echo is the return to your ear by one sound wave at least 0.15 s after the sound has been transmitted.

7 When waves travel in a tube such as a stethoscope, they can be reflected off the walls of the tube so that they can be guided along a non-linear path.

APPLYING

8 This would be achieved if the walls of the tube were made from a high-density material and if the angle of incidence was as great as possible.

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9 To reduce the impact of echoes and reverberations as much as possible, the walls of a concert hall should be made of a low-density material that will readily allow incident waves to be transmitted through them rather than reflected. This property could be increased by ensuring the angle of incidence is as small as possible by correctly orientating the walls to the source of sound.

16.7 SECTION REVIEW

REMEMBERING

1 The refraction of waves is when waves change direction when they strike an interface with another medium at an angle other than 90°. The speed and wavelength of the wave also change.

2 The apparent position is the position that an object appears to an observer; it may be different from its actual position due the refraction of its light waves.

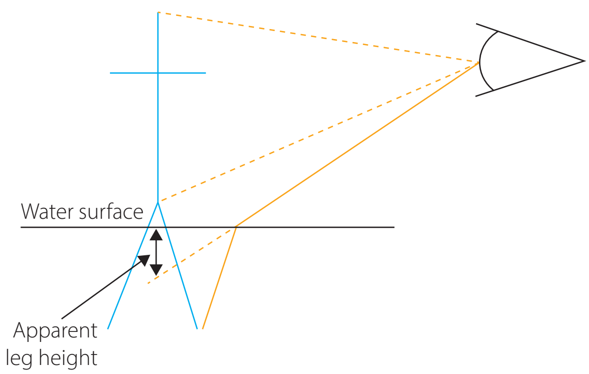
3 Atmospheric refraction is the refraction of light rays as they pass through Earth's atmosphere.

UNDERSTANDING

4 Refraction will occur whenever the density of the two media through which the wave travels is different.

5 When a wave is refracted into a denser material, the wavelength and velocity of the wave will decrease, while the period and frequency remain unchanged.

6 The refraction of light waves coming from the leg causes the apparent position of the feet to be higher than if there was no refraction.



16.8 SECTION REVIEW

REMEMBERING

1 Diffraction is the bending of waves around an obstacle.

2 Diffraction is used to create calmer waters in a harbour; the section of incoming water waves that pass through the harbour walls spread in a circular pattern and thus dissipate their energy.

UNDERSTANDING

3 Reflection is the rebounding of waves off a boundary between two media, refraction is the bending of a wave as it passes through the boundary between two media and diffraction is the bending of a wave around an obstacle.

4 The effect of diffraction can be increased by making the wavelength of the incoming wave greater than the width of the obstacle.

APPLYING

5 In the absence of diffraction, the sound would be either reflected by the tree or absorbed by the tree and no sound would be heard as there is nothing else for it to rebound back to the observer from. However, if the wavelength of the sound is greater than the width of the tree, the sound waves will diffract around the tree and reach the ears of the observer.

16.9 SECTION REVIEW

REMEMBERING

1 a Interference of waves occurs when two or more waves pass through the same space at the same time

b Constructive interference occurs when the peaks of two waves overlap to create an overall particle displacement equal to the amplitude of both waves added together

c Destructive interference occurs when the peak of one wave overlaps with the trough of another to create an overall particle displacement of less than the amplitude of either wave.

2 Two waves are considered in-phase if they are of the same wavelengths and the crests of each wave overlap, while they are considered to be out-of-phase if they are of the same wavelength and the crest of one wave overlaps with the trough of the other.

UNDERSTANDING

3 The principle of superposition states that when two waves pass through the same place at the same time, that they will create a particle displacement equal to the sum of the particle displacements of the two individual waves at that point in time.

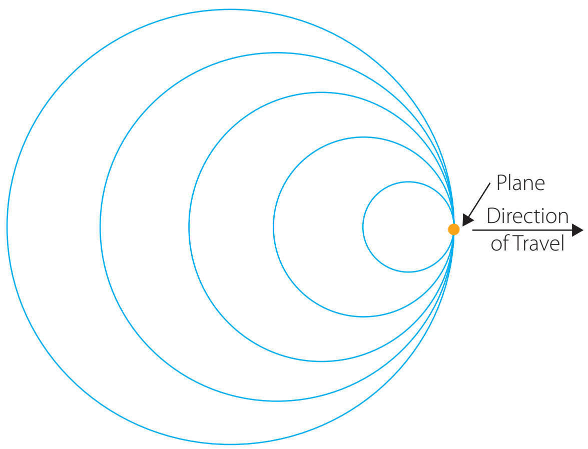
4 The Doppler affect occurs because the velocity of the source of the sound waves can alter the wavelength of the sound as heard by an observer. When the siren is approaching the observer, the wavelength is decreased which increases the frequency or pitch. As the siren moves away from the observer, the wavelength is increased which decreases the frequency or pitch.

APPLYING

5 The maximum amplitude occurs when constructive interference or the overlap of the two crests occurs. At this point the displacement will be equal to the sum of the individual amplitudes, or 6 cm + 9 cm = 15 cm

6 The minimum amplitude will occur when destructive interference occurs. At this point, the displacement will be equal to the difference between the two amplitudes, or 9.0 cm – 6.0 cm = 3.0 cm.

7



16.10 SECTION REVIEW

REMEMBERING

1 A standing wave is a wave that oscillates in place, without transmitting energy along its extent.

2 At a node, the total particle displacement is equal to zero at all times, while at an antinode, the particle displacement oscillates between the maximum and minimum values.

3 The distance between a node and an anti-node is equal to one quarter of a wavelength.

UNDERSTANDING

4 Node = destructive interference, antinode = constructive interference

5 Each piano string has a different length and/or density, which affects not only the speed of the wave but the wavelength of the standing wave patterns that can form on them. Both of these features affect the frequency of the standing wave that is emitted as a sound wave.

CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 a The intensity of a wave is a measure of the energy per unit time that is travelling through a unit of area perpendicular to the direction of travel.

b The amplitude of a wave is the maximum displacement of a particle in a wave from its mean position.

c A wave front is an imaginary surface joining all points in space that are reached at the same instant by a wave propagating through a medium.

d The period of a wave is the time it takes before a wave repeats itself.

e The frequency of a wave is the number of whole waves or cycles in one second.

f The wavelength of a wave is the distance travelled by a wave before it repeats itself.

g The wave velocity is the velocity at which wave crests move through a medium.

h Mechanical waves are waves that require a physical substance to be able to propagate.

i A transverse wave is a wave whose particles oscillate about a mean position perpendicular to the direction of travel by the wave.

j A longitudinal wave is a wave whose particles oscillate around a mean position in the same line as the direction of travel of the wave.

k A compression is a region of high pressure in a mechanical wave.

l A rarefaction is a region of lower pressure in a mechanical wave.

m The seismic focus is the underground point from which earthquake energy is released.

n The epicentre is the point on Earth's surface directly above the seismic focus.

o Body waves are seismic waves that travel through the body of Earth.

p An S wave is a transverse earthquake wave, which shakes Earth in directions perpendicular to the direction that the wave is travelling; also known as a shear wave.

q A P wave is a longitudinal earthquake compression wave that passes through the body of Earth.

r A seismometer is a device that records the strength and frequency of seismic waves.

2 The intensity of a wave decreases in inverse proportion to the square of the distance from the source.

3 The principle of superposition states that when two waves pass through the same point at the same time, they will create a particle displacement equal to the sum of the particle displacements of the individual waves at that point.

CATEGORY QUESTIONS

4 a Primary (P) wave

b Secondary (S) or shear wave

5 Primary (P) waves are created by the back and forward oscillation of Earth at the source, and their energy propagates outward in a direction parallel to the oscillation of the particles of Earth. Secondary (S) shear waves result from the upward and downward motion of Earth at the source and their energy propagates outward in a direction that is perpendicular to the oscillations of the particles of Earth.

6 The major factors that affect the strength of the seismic wave felt on Earth include; the initial intensity of the disturbance at the seismic focus, the distance travelled by the wave, the material through which the wave has travelled and the type of wave experienced.

7 The factors that affect the speed at which the seismic wave will travel through Earth include the type of wave (S or P) and the density of the medium through which they are travelling.

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ELABORATION QUESTIONS

8 Answers will vary but should focus on comparisons between the arrival times of P and S waves and changes in intensity as measured from numerous seismometers.

9 The model of tectonic plates suggests that the surface of Earth consists of plates that move relative to each other. This model suggests that there should be a disturbance in Earth as the plates interact with each other as they slide against, under, over, together or apart.

10 Answers will vary but should include discussion of:
- building designs which dissipate the energy of earthquakes
- building population centres away from seismically active areas
- improved ability to predict seismic activity.

EVIDENCE QUESTIONS

11 Answers will vary depending on research conducted.

12 The existence of seismic waves is good evidence that the surface of Earth consists of plates that are interacting.

13 The strongest pieces of evidence for the tectonic plate model include:
- Sea floor magnetism – regions of magnetically aligned sea floor at equal distance from areas of sea floor spreading
- Fossil evidence – Fossils of similar species have been found on separated continents suggesting that they were in contact at one time

END-OF-CHAPTER EXAM

1 D

2 A

3 D

4 C

5 C

6 B

7 A

8 Diffraction

9 Refraction

10 Antinode

11 The motion of the energy of a transverse wave is perpendicular to the oscillation of the particles of the medium

12 S waves are transverse waves while P waves are longitudinal waves. P waves travel faster through Earth than S waves.

13 The principle of superposition states that when two waves pass through the same point at the same time, they will create a particle displacement equal to the sum of the particle displacements of the individual waves at that point.

14 $v = \frac{\lambda}{T}$

Apply the wave velocity formula

$v = \frac{5.5\,\text{m}}{5\,\text{s}}$

Insert known values

$v = 1.1\,\text{m s}^{-1}$

Give the answer to the correct number of significant figures

15 $v = f\lambda$

Apply the wave velocity formula

$\lambda = \frac{v}{f}$

Rearrange the formula for the required λ

$\lambda = \frac{343\,\text{m s}^{-1}}{215\,\text{Hz}}$

Insert known values

$\lambda = 1.5953\,\text{m}$

Calculate the answer

$\lambda = 1.60\,\text{m}$

Give the answer to the correct number of significant figures

16 Sound waves are longitudinal waves consisting of compressions and rarefaction of air that produce regions of high and low air pressure. These wave features interact with the ear drum to make it vibrate. The vibrations from the eardrum travel down the bones of the middle ear and ultimately cause the fluid in the inner ear to vibrate. This vibration is picked up by small hairs in the cochlear that transmit electrical signals via nerves to the brain.

17 The speed of a wave is dependent upon the elastic properties of the medium through which it is travelling. A specific amount of energy will travel at different velocities in different media due to differences in this elastic property.

18 Standing waves occur as a result of the reflection of continuous waves at a boundary with a higher density medium. The waves reflect in an inverted position and interfere with the oncoming wave. At specific wavelengths and media lengths, this will create patterns of nodes and anti-nodes that do not appear to change over time.

19 $d = v \times t$

Apply the distance formula

$d = (f\lambda) \times t$

Substitute the velocity formula, $v = f\lambda$

$d = 2400\,\text{Hz} \times 0.143\,\text{m} \times 3\,\text{s}$

Insert known values

$d = 1029.6\,\text{m}$

Calculate the answer

$d = 1.0 \times 10^3\,\text{m}$

Give the answer to the correct number of significant figures

20 a $A = 0.6\,\text{m}$

b $T = 6.67 \times 10^{-3}\,\text{m}$

c $f = \frac{1}{T} = \frac{1}{6.67 \times 10^{-3}\ \text{m}} = 150\ \text{Hz}$

d $\lambda = 1.5\ \text{m}$

e $v = f\lambda = 150\ \text{Hz} \times 1.5\ \text{m} = 225\ \text{m s}^{-1}$

CHAPTER 17: SOUND

17.1 SECTION REVIEW

REMEMBERING

1 a The natural frequency of an object is the vibration frequency that occurs when the object is displaced from its equilibrium position and then left to vibrate by itself.

b The forced vibration of an object in contact with another vibrating object.

c Resonance occurs when an object is induced to oscillate at its natural frequency by the vibration of another object that is also vibrating at that natural frequency.

2 A natural vibration is the frequency that an object will vibrate at without interference from any other vibration, whereas a forced vibration is the vibration an object will vibrate at due to the presence of another vibrating object.

3 The driving frequency of a resonating system is the vibration of an object that causes a second object to undergo resonance at the resonant frequency.

4 Blowing across a bottle top provides waves of many frequencies into the bottle and if one of these frequencies coincides with the resonant frequency of the bottle, the bottle itself will vibrate at this frequency and emit a tone.

UNDERSTANDING

5 The condition for resonance to occur is that the driving frequency matches the natural frequency

6 A standing wave has this name because it appears to 'stand'; that is, its nodes and anti-nodes do not appear to travel.

APPLYING

7 A tuning fork will only cause another tuning fork to vibrate at its natural frequency if the first tuning fork is vibrating at the natural frequency of the second and if there is a medium for the vibration to travel through efficiently.

8 If a sound wave with a frequency matching the natural frequency of the glass is played near the glass, the energy of the sound is transmitted very efficiently to the glass, causing it to vibrate with a large amplitude that may overcome the bonds holding the particles of the glass together. If this happens, the glass will shatter,

17.2 SECTION REVIEW

REMEMBERING

1 The second mode of vibration has a frequency double that of the fundamental mode. It also has a wavelength half that of the fundamental and has one more node and anti-node.

UNDERSTANDING

2 The energy of the wave is not destroyed during the formation of a standing wave, rather it results in an altered pattern of propagation. Although the nodes have a displacement of zero at all times, the anti-nodes will have an increased amplitude compared to that of the original wave.

3 a $\frac{\ell}{2}$

b $\frac{\ell}{2}$

c $\frac{\ell}{4}$

4 B and C

APPLYING

5 a $\ell = n\frac{\lambda_n}{2}$

Apply equation

$\lambda_n = \frac{2\ell}{n}$

Rearrange for the required λ

$\lambda_1 = \frac{2 \times 0.8\ \text{m}}{1}$

Insert known values

$\lambda_1 = 1.6\ \text{m}$

Calculate the answer to the correct number of significant figures

b $v = f\lambda$

Apply the wave velocity equation

$f = \frac{v}{\lambda}$

Rearrange for the required f

$f = \frac{200\ \text{m s}^{-1}}{1.6\ \text{m}}$

Insert known values

$f = 125\ \text{Hz}$

c By the equation $f_1 = n\frac{v}{2\ell}$, it can be seen that decreasing the length of the wire will result in an increase in the fundamental frequency of the standing wave produced.

d Increasing the slotted masses would only produce a tone if they were placed at the nodes of varying harmonics of the system. By the equation $f_n = nf_1$ it can be seen that by placing the slotted masses at various nodes (effectively increasing the value of n) the frequency produced would be higher than the fundamental frequency.

ANALYSING

6 $\ell = n\frac{\lambda_n}{2}$

Apply equation

$\lambda_n = \frac{2\ell}{n}$

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Rearrange for the required λ

$$\lambda_1 = \frac{2 \times 0.12\,\text{m}}{1}$$

Insert known values

$$\lambda_1 = 0.24\,\text{m}$$

Calculate the answer to the correct number of significant figures

7 From the problem, we can construct two equations:

$$f_n = 300\,\text{Hz} = nf_1 \qquad (1)$$

and

$$f_{n+1} = 360\,\text{Hz} = (n+1)f_1 \qquad (2)$$

Rearrange equation (1) for n

$$n = \frac{300\,\text{Hz}}{f_1}$$

Rearrange equation (2) for n

$$n = \frac{360\,\text{Hz} - f_1}{f_1}$$

Equate the two n's

$$\frac{300\,\text{Hz}}{f_1} = \frac{360\,\text{Hz} - f_1}{f_1}$$

Cancel the denominators on both sides

$$300\,\text{Hz} = 360\,\text{Hz} - f_1$$

Rearrange to make the required f_1 the subject

$$f_1 = 360\,\text{Hz} - 300\,\text{Hz}$$

Calculate the answer

$$f_1 = 60\,\text{Hz}$$

17.3 SECTION REVIEW

REMEMBERING

1 a An open pipe has both ends open to the external atmosphere, while a closed pipe has one end open to the external atmosphere and the other end closed.

b The wavelength of the fundamental frequency of an open pipe is two times the length of the pipe, whereas the wavelength of the fundamental frequency of a closed pipe is equal to four times the length of the pipe.

UNDERSTANDING

2 D

3 C

APPLYING

4 Apply the closed air pipe frequency formula

$$f_n = (2n-1)\frac{v}{4\ell}$$

Rearrange the equation for the required v

$$v = \frac{4f_n\ell}{(2n-1)}$$

Insert known values

$$v = \frac{4 \times 256\,\text{Hz} \times 0.31\,\text{m}}{(2 \times 1 - 1)}$$

Calculate the answer

$$v = 317.44\,\text{m}\,\text{s}^{-1}$$

Give the answer to the correct number of significant figures

$$v = 320\,\text{m}\,\text{s}^{-1}$$

5 Apply the closed air pipe frequency formula

$$f_n = (2n-1)\frac{v}{4\ell}$$

Rearrange the equation for the required ℓ

$$\ell = (2n-1)\frac{v}{4f_n}$$

Insert known values

$$\ell = (2 \times 1 - 1)\frac{340\,\text{m}\,\text{s}^{-1}}{4 \times 5000\,\text{Hz}}$$

Calculate the answer

$$\ell = 0.017\,\text{m}$$

CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 a The natural frequency of an object is the vibration frequency that occurs when the object is displaced from its equilibrium position and then left to vibrate by itself.

b The forced vibration of an object in contact with another vibrating object.

c Resonance occurs when an object is induced to oscillate at its natural frequency by the vibration of another object which is also vibrating at that natural frequency.

d The driving frequency of a resonating system is the vibration of an object that causes a second object to undergo resonance.

e The resonant frequency of an object is any of the possible standing wave frequencies of the object.

f A harmonic is the frequency of the standing wave pattern.

g An open pipe is a pipe that is open at both ends.

h A closed pipe is a pipe that is open at one end and closed at the other end.

CATEGORY QUESTIONS

2 If the frequency of vibration of one object matches the resonant frequency of another object, then the second object will begin to vibrate at that frequency in a very efficient manner.

3 Answers will vary but may include:

- tuning forks
- strings of instruments
- water blown over the top of a bottle.

4 The transfer of energy from the object emitting the driving frequency to the object that is made to resonate is taking place in a very efficient manner, meaning that it will have a higher amplitude and be sustained for a longer period than if the driving frequency is at any other frequency.

5 A vibrating object emits a sound wave that is a longitudinal wave consisting of compressions and rarefactions of air that produce regions of high and low air pressure. These wave features interact with the eardrum to make it vibrate. The vibrations from the eardrum travel down the bones of the middle ear where and ultimately cause the fluid in the inner ear to vibrate. Small hairs in the cochlear pick up this vibration and transmit electric signals via nerves to the brain.

6 The wavelengths of the resonant frequencies that can exist in an open-air column follow the pattern: $\frac{\ell}{2}, \ell, \frac{3\ell}{2}, 2\ell\ldots,$ whereas the wavelengths of the resonant frequencies that can exist in air columns closed at one end follow the pattern:

$\frac{\ell}{4}, \frac{3\ell}{4}, \frac{5\ell}{4}, \frac{7\ell}{4} \ldots$

ELABORATION QUESTIONS

7 Answers will vary but should discuss the fact that the wind provided a driving frequency very similar to the natural frequency of the Tacoma Narrows Bridge. The efficient transfer of energy in this system resulted in the bridge vibrating at its resonant frequency with a large enough amplitude to break its structure.

8 Standing waves on a string have nodes, which are points where the particle displacement is zero at all times. Touching the string at this point will still allow the energy of the standing wave to travel and will therefore not bring the vibration to a stop.

9 The frequency of greatest sensitivity for a cat (32 000–500 000 Hz) is considerably higher than that for a human (2000–5000 Hz). This suggests that the length of a cat's ear canal is shorter, according to the formula: $\ell = (2n-1)\frac{v}{4f_n}$.

EVIDENCE QUESTIONS

10 Answers will vary but may include:

- investigation of the frequency of the dominant winds in the area to ensure the natural frequency of the bridge was different
- adequate damping of the bridge, to ensure that the energy of vibration was efficiently removed from the bridge.

11 Answers will vary depending on research conducted.

END-OF-CHAPTER EXAM

1 B

2 C

3 B

4 A

5 Resonance

6 Harmonic

7 A forced vibration is the vibration that occurs in an object when it is forced to vibrate by another vibrating object.

8 The factors that affect the natural frequency of an object include its length and the velocity of the wave in the object.

9a Apply the equation

$f_n = nf_1$

So, the frequencies of the next three harmonics are

$f_2 = 2\times f_1 = 2\times 15\,\text{Hz} = 30\,\text{Hz}$

$f_3 = 3\times f_1 = 3\times 15\,\text{Hz} = 45\,\text{Hz}$

$f_4 = 4\times f_1 = 4\times 15\,\text{Hz} = 60\,\text{Hz}$

b Apply the equation

$f = n\frac{v}{2\ell}$

Rearrange for the required v

$v = \frac{2\ell f_n}{n}$

Insert known values:

$v = \frac{2\times 3\,\text{m}\times 15\,\text{Hz}}{1}$

Calculate the answer

$v = 90\,\text{m}\,\text{s}^{-1}$

c Apply the equation

$\ell = n\frac{\lambda_n}{2}$

Rearrange for the required λ

$\lambda_n = \frac{2\ell}{n}$

Insert known values

$\lambda_n = \frac{2\times 3\,\text{m}}{1}$

Calculate the answer to the correct number of significant figures

$\lambda_1 = 6.0\,\text{m}$

10 Apply the formula

$f_n = n\frac{v}{2\ell}$

Rearrange for the required ℓ

$\ell = n\frac{v}{2f_n}$

Insert known values

$\ell = 1\times\frac{343\,\text{m}\,\text{s}^{-1}}{2\times 280\,\text{Hz}}$

Calculate the answer

$\ell = 0.61\,\text{m}$

11 a Apply the equation

$\ell = (2n-1)\frac{\lambda_n}{4}$

Rearrange for the required λ

$\lambda_n = \frac{4\ell}{(2n-1)}$

Insert known values and calculate the answers

$\lambda_1 = \frac{4\times 2\,\text{m}}{(2\times 1-1)} = 8.0\,\text{m}$

$\lambda_2 = \frac{4\times 2\,\text{m}}{(2\times 2-1)} = 2.67\,\text{m}$

$\lambda_3 = \frac{4\times 2\,\text{m}}{(2\times 3-1)} = 1.6\,\text{m}$

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b Apply the equation

$$f_n = \frac{v}{\lambda_n}$$

Calculate the answers

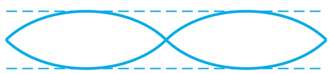
$$f_1 = \frac{340\,\text{m s}^{-1}}{\lambda_1} = \frac{340\,\text{m s}^{-1}}{8\,\text{m}} = 42.5\,\text{Hz}$$

$$f_2 = \frac{340\,\text{m s}^{-1}}{\lambda_2} = \frac{340\,\text{m s}^{-1}}{2.667\,\text{m}} = 127\,\text{Hz}$$

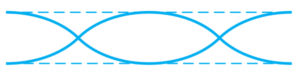
$$f_3 = \frac{340\,\text{m s}^{-1}}{\lambda_3} = \frac{340\,\text{m s}^{-1}}{1.6\,\text{m}} = 213\,\text{Hz}$$

12 When air is blown through the mouthpiece, many frequencies of sounds are imparted to the open pipe. These waves will reflect off the end opposite the mouthpiece and interfere according to the principle of superposition with the oncoming waves. Most of these waves will destructively interfere along the body of the clarinet; however, the fundamental and harmonic frequencies will interfere in a way that will create standing wave patterns. These frequencies can be altered by using the various fingerings of the clarinet.

13 a Pressure variation



b Particle displacement



14 Apply the equation

$$f_n = n\frac{v}{2\ell}$$

Insert known values to calculate the fundamental frequency emitted by the pipe

$$f_1 = 1 \times \frac{340\,\text{m s}^{-1}}{2 \times 2.2\,\text{m}} = 77.27\,\text{Hz}$$

Since the fundamental frequency is within the range of human hearing, humans will be able to discern the frequency when $n = 1$

Rearrange the equation for n

$$n = \frac{2\ell f_n}{v}$$

Insert known values for the highest frequency of human hearing

$$n = \frac{2 \times 2.2\,\text{m} \times 20\,000\,\text{Hz}}{340\,\text{m s}^{-1}} = 258.82$$

This means that the highest harmonic that will be heard is $n = 258$

Therefore, the human ear will be able to hear 258 vibrational modes of the pipe

15 From the problem, construct two equations

$$f_n = 350\,\text{Hz}(2n-1)f_1 \quad (1)$$

and

$$f_{n+1} = 450\,\text{Hz}(2(n+1)-1)f_1 \quad (2)$$

Rearrange equation (1) for n

$$n = \frac{1}{2}\left(\frac{350\,\text{Hz}}{f_1} + 1\right)$$

Rearrange equation (2)

$$450\,\text{Hz} = (2n+1)f_1$$

Rearrange for n

$$n = \frac{1}{2}\left(\frac{450\,\text{Hz}}{f_1} - 1\right)$$

Equate the two n's

$$\frac{1}{2}\left(\frac{350\,\text{Hz}}{f_1} + 1\right) = \frac{1}{2}\left(\frac{450\,\text{Hz}}{f_1} - 1\right)$$

Cancel the $\frac{1}{2}$'s on both sides

$$\frac{350\,\text{Hz}}{f_1} + 1 = \frac{450\,\text{Hz}}{f_1} - 1$$

Collect like terms

$$\frac{450\,\text{Hz}}{f_1} - \frac{350\,\text{Hz}}{f_1} = 1 + 1$$

Perform algebra

$$\frac{100\,\text{Hz}}{f_1} = 2$$

Rearrange for the required f_1

$$f_1 = \frac{100\,\text{Hz}}{2}$$

Calculate the answer

$$f_1 = 50\,\text{Hz}$$

CHAPTER 18: LIGHT

18.1 SECTION REVIEW

REMEMBERING

1 The wave model of light, the ray model of light and the particle model of light

2 A photon is the particle that is used to describe some of the behaviour of light.

UNDERSTANDING

3 The ray model assumes light travels in straight lines that change direction when they interact with matter; the wave model assumes that light travels as a wave through a medium or a vacuum with a velocity dependent on the properties of the medium; the particle model assumes that light travels in the form of particles that can be absorbed when they interact with matter.

4 'What is light?' is a misleading question as light exhibits wave–particle duality. Instead, the question that should be asked is 'How does light behave?'.

18.2 SECTION REVIEW

REMEMBERING

1 The electromagnetic wave model suggests that light is a three-dimensional transverse wave consisting of oscillations in the electric and magnetic fields of its medium.

2 A luminous material emits light while a non-luminous material reflects light.

UNDERSTANDING

3 The electromagnetic wave model is very useful in describing the behaviour of light in many situations, including polarisation, reflection, refraction and diffraction.

4 Two adjacent light rays that are emanating from a very distant point source can be considered parallel, as their relative angles of travel are very similar.

5 If light is considered as a wave, the intensity of light as a function of its distance from the source can be modelled using the same concepts as mechanical waves. That is, the intensity of light is indirectly proportional to the square of the distance from the source.

APPLYING

6 Apply the formula

$$c = f\lambda$$

Rearrange for the required λ

$$\lambda = \frac{c}{f}$$

Insert known values

$$\lambda = \frac{3.0\times10^{8}\ \mathrm{m\,s^{-1}}}{5.0\times10^{14}\ \mathrm{Hz}}$$

Calculate the answer

$$\lambda = 6.0\times10^{-7}\ \mathrm{m}$$

7 Apply the intensity formula at the first point

$$I_1 = \frac{P}{r_1^2} \qquad (1)$$

Apply the intensity formula at the second point

$$I_2 = \frac{P}{r_2^2} \qquad (2)$$

Write down the relationship between r_1 and r_2

$$r_2 = 1.5\times r_1 \qquad (3)$$

Substitute equation (3) into equation (2)

$$I_2 = \frac{P}{(1.5r_1)^2}$$

Expand the brackets

$$I_2 = \frac{P}{2.25\times r_1^2} = \frac{1}{2.25}\times\frac{P}{r_1^2} \qquad (4)$$

Substitute equation (1) into equation (4)

$$I_2 = \frac{1}{2.25}\times I_1$$

Insert known values

$$I_2 = \frac{1}{2.25}\times 200\ \mathrm{W\,m^{-2}}$$

Calculate the answer

$$I_2 = 89\ \mathrm{W\,m^{-2}}$$

ANALYSING

8 To calculate the velocity of light in the experiment, both the distance travelled and the time taken need to be known. The distance could be physically measured, and the time taken could be calculated by measuring the rotational velocity of the wheel when it allows a light ray to pass through its teeth.

18.3 SECTION REVIEW

REMEMBERING

1 Polarisation is the orientation in one direction of the electrical part of electromagnetic waves perpendicular to the direction of travel.

2 Longitudinal waves cannot be polarised as their oscillations can only be in one direction: parallel to the direction of travel.

UNDERSTANDING

3 Both the polariser and the analyser only allow light waves of one polarisation to pass. The polariser selects the orientation of interest and the analyser is used to show the decrease in intensity at all other orientations.

4 Polarised sunglasses reduce the intensity of light reaching the eyes by reflecting all light that is not aligned with the direction of the polariser.

APPLYING

5 This occurs because disturbances in the electric field of the media through which light waves are travelling oscillate in one orientation, so if the analyser starts from dark, it must be orientated perpendicularly to the orientation of the electric field. A quarter turn will make the orientations parallel and light will pass. Another quarter turn will once again cause the orientations to be perpendicular.

18.4 SECTION REVIEW

REMEMBERING

1 The incident ray, the normal to the surface at the point of reflection and the reflected ray all lie in the same plane

The angle of incidence is equal to the angle of reflection.

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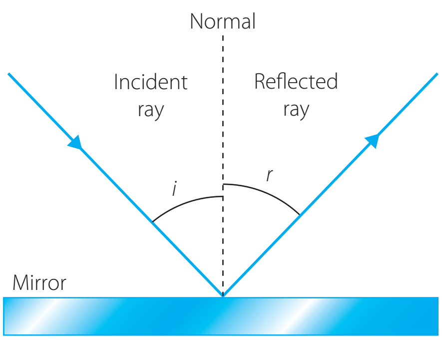

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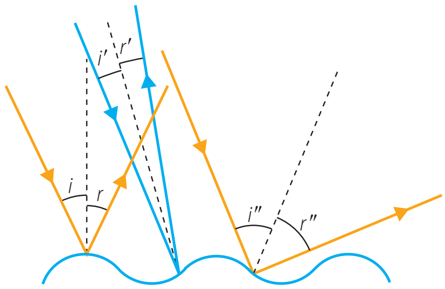
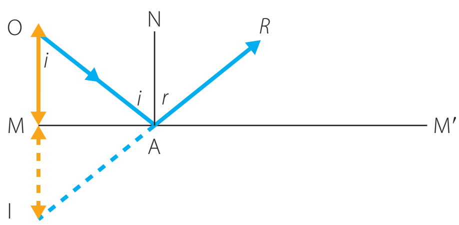


UNDERSTANDING

3



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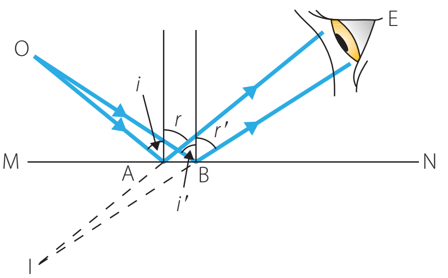
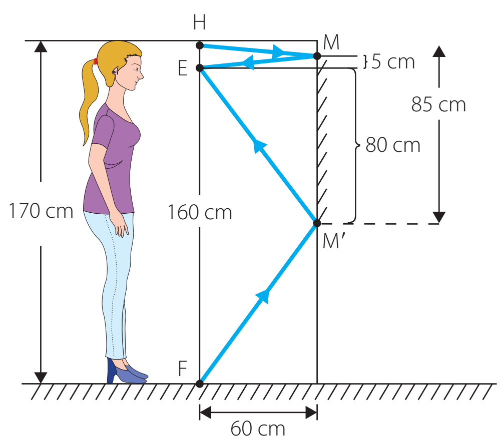


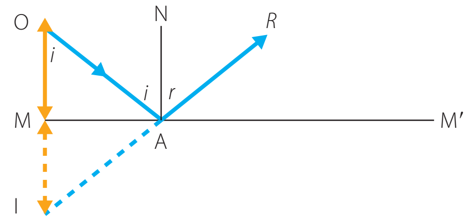
ANALYSING

5



From the image we see that the minimum height is 85 cm.

6



In ΔAMO:

∠AOM = *i* (alternative angle between parallel lines AN and MO)

∠OAM = 90° – *i* (complementary angles in right triangle)

along the line IAR:

∠MAI + (90° – *i*) + *i* + *r* = 180° (angles on a straight line)

⇒ ∠MAI + 90° + *i* = 180° (*r* = *i*)

⇒ ∠MAI = 90° – *i*

In ΔAMI:

∠MIA = *i* (complementary angles in right triangle)

⇒ ΔAMO and ΔAMI are similar (all angles the same)

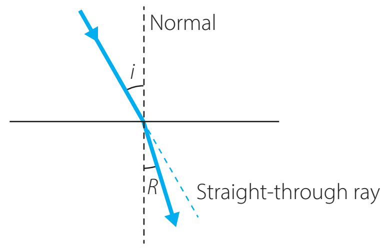
⇒ ΔAMO and ΔAMI are congruent (AM is common)

⇒ MO = MI

18.5 SECTION REVIEW

REMEMBERING

1



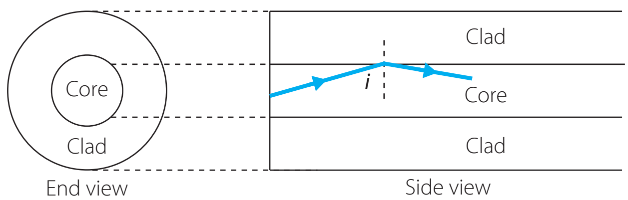
2 Snell's law: $\frac{\sin i}{\sin r}$ = constant, *n*

3 The absolute refractive index is $\frac{\sin i}{\sin r}$ for light travelling from a vacuum into the medium. The refractive index varies slightly with wavelength

UNDERSTANDING

4 The absolute refractive index is relative to a vacuum, taken to be the absolute medium.

5



6 A concave lens is a lens which is thinner in the centre and a convex lens is thicker in the centre. A concave lens diverges incoming parallel rays and a convex lens converges incoming parallel rays.

APPLYING

7 a i Apply equation:

$c = f\lambda$

Rearrange for the required f

$f = \frac{c}{\lambda}$

Insert known values

$f = \frac{3.0 \times 10^8 \text{ m s}^{-1}}{981 \times 10^{-9} \text{ m}}$

Calculate the answer

$f = 3.06 \times 10^{14}$ Hz

ii The frequency remains constant in both media so

$f = 3.06 \times 10^{14}$ Hz

b Apply Snell's law

$\frac{v_1}{v_2} = \frac{n_2}{n_1}$

Rearrange for the required v_2

$v_2 = v_1 \frac{n_1}{n_2}$

Insert known values

$v_2 = 3.0 \times 10^8 \text{ m s}^{-1} \times \frac{1.00}{1.39}$

Calculate the answer

$v_2 = 2.16 \times 10^8 \text{ m s}^{-1}$

c Apply Snell's law

$\frac{\sin i}{\sin r} = \frac{n_2}{n_1}$

Rearrange for the required $\sin r$

$\sin r = \sin i \frac{n_1}{n_2}$

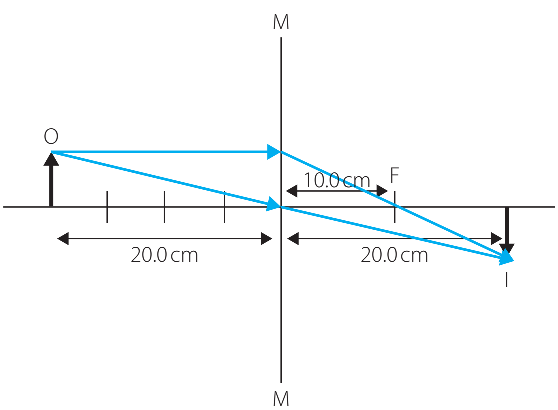
Insert known values

$\sin r = \sin 25° \times \frac{1.00}{1.39}$

Calculate the answer

$r = 17.7°$

8



The object lies a distance of 20.0 cm on the opposite side of the lens

ANALYSING

9 a Apply Snell's law for total internal reflection

$\frac{\sin \theta_c}{\sin 90°} = \frac{n_2}{n_1}$

Rearrange for $\sin \theta_c$

$\sin \theta_c = \sin 90° \times \frac{n_2}{n_1}$

Insert known values

$\sin \theta_c = \sin 90° \times \frac{1.480}{1.495}$

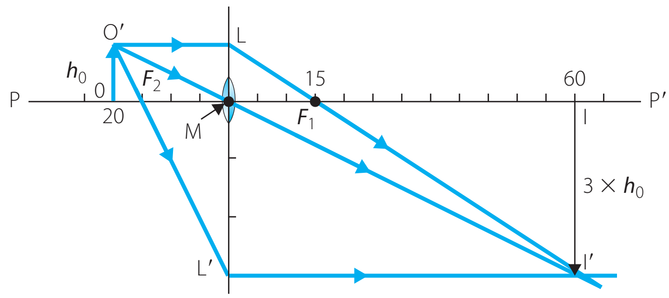
Calculate the answer

$\theta_c = 81.88°$

b $r = 90° - 81.88°$

$r = 8.12°$

10

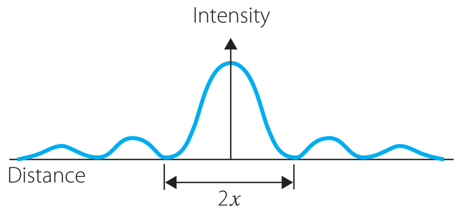


The focal distance of the lens is 15 cm

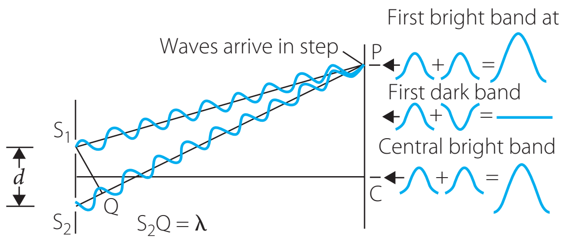
18.6 SECTION REVIEW

REMEMBERING

1 a



b



2 a Path difference = $n\lambda$ for n values of 1, 2, 3, …

b Path difference = $(n - \frac{1}{2})\lambda$ for n values of 1, 2, 3, …

UNDERSTANDING

3 The distance between consecutive bright and dark fringes decreases.

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APPLYING

4 The second minimum (destructive interference) corresponds to the path difference associated with $n = 2$

Apply the destructive interference formula path difference = $(2n-1)\frac{\lambda}{2}$

Rearrange for the unknown λ

$$\lambda = \frac{2 \times \text{path difference}}{(2n-1)}$$

Insert known values

$$\lambda = \frac{2 \times 750\,\text{nm}}{(2 \times 2 - 1)}$$

Calculate the answer

$\lambda = 500\,\text{nm}$

CHAPTER REVIEW QUESTIONS

DETAIL QUESTIONS

1 a The ray model of light is a model that describes light as travelling in rays that change direction during interactions with matter.

b The wave model of light is a model of that describes light as travelling as waves.

c The particle model of light is a model that describes light as travelling as particles (photons)

d A photon is a particle of light as described by the particle model of light.

e Electromagnetic radiation is energy that travels as waves and moves at the speed of light.

f Reflection is the rebounding of waves as they strike a boundary between two media.

g Refraction is the bending of light as they are transmitted into a different medium.

h Refrangibillity is a measure of how much refraction will occur when light moves into a particular material from a vacuum.

i Diffraction is the bending of waves around an obstacle.

2 The law of reflection states that the angle of incidence of a wave is equal to the angle of reflection.

3 Light cannot be modelled as a mechanical wave because it can travel in a vacuum. Mechanical waves all require a medium through which to transfer their energy.

CATEGORY QUESTIONS

4 When light is incident upon a transparent object, some of it will be reflected at the boundary and some will be transmitted through the boundary. According to the law of reflection, the angle of reflection of the portion that is reflected will equal the angle of incidence and the frequency, wave length and wave velocity of the reflected wave will be the same as the incident wave. Snell's law states that the transmitted wave will undergo refraction as it passes into the new medium. The refracted wave will have the same frequency as the incident wave; however, its wave velocity and wavelength will decrease in the second medium. In addition, the angle of refraction will be smaller than the angle incidence.

5 As the degree of refraction is wavelength dependent, the white light will be seen to separate into its constituent wavelengths that will all travel at slightly different angles, while the monochromatic light will all travel along the same path.

6 The lens of the eye consists of a converging convex lens with a focal point on the retina of the eye. This lens focuses incoming light rays to the sensors on the retina.

7 Light is said to obey wave–particle duality, because in some instances its behaviour obeys wave mechanics and cannot be described using the particle model, whereas in other situations its behaviour obeys particle mechanics and cannot be described using the wave model.

8 Light is known to undergo the phenomenon of diffraction when it is incident upon an obstacle. This is a purely wave-like phenomenon.

9 When light undergoes the photoelectric effect, it transfers momentum to electrons, which is a phenomenon that can only be described using particle mechanics.

ELABORATION QUESTIONS

10 When the Sun is near the horizon, the phenomenon of refraction alters its apparent position and shape as well as its dominant wavelengths.

11 Alterations in the strength of the eye muscles can change the shape of the lens, which leads to an alteration of the focal length of the lens. This can lead to difficulties in focusing on objects that are near to the eye or far away from the eye.

12 If light were a particle and did not obey wave mechanics, no diffraction would occur and the double-slit experiment would result in two bright fringes on the screen.

13 Answers will vary.

EVIDENCE QUESTIONS

14 Answers will vary.

15 Answers will vary.

END-OF-CHAPTER EXAM

1 C

2 C

3 A

4 C

5 A

6 The first harmonic

7 Virtual

8 Chromatic dispersion occurs because white light is separated into its constituent wavelengths as it is refracted through a medium. This is because the refractive index of a medium differs for each wavelength.

9 If the angle of refraction is greater than the angle of incidence, it can be deduced that the light is being transmitted into a medium of a lower refractive index. In this situation, the frequency remains the same, while the wavelength and wave velocity increase.

10 Apply the intensity formula at the first point

$$I_1 = \frac{P}{r_1^2} \qquad (1)$$

Apply the intensity formula at the second point

$$I_2 = \frac{P}{r_2^2} \qquad (2)$$

Write down the relationship between r_1 and r_2

$$r_2 = 3 \times r_1 \qquad (3)$$

Substitute equation (3) into equation (2)

$$I_2 = \frac{P}{(3r_1)^2}$$

Expand the brackets

$$I_2 = \frac{P}{9r_1^2} = \frac{1}{9} \times \frac{P}{r_1^2} \qquad (4)$$

Substitute equation (1) into equation (4)

$$I_2 = \frac{1}{9} \times I_1$$

Insert known values

$$I_2 = \frac{1}{9} \times 400\,\mathrm{W\,m^{-2}}$$

Calculate the answer

$$I_2 = 44\,\mathrm{W\,m^{-2}}$$

11 Calculate the distance travelled by light using the distance–velocity formula

$$s = v \times t = 3 \times 10^8\,\mathrm{m\,s^{-1}} \times 0.01\,\mathrm{s} = 3 \times 10^6\,\mathrm{m}$$

Calculate the time that it takes sound to travel this distance by rearranging the distance–velocity formula

$$t = \frac{s}{v} = \frac{3 \times 10^6\,\mathrm{m}}{343\,\mathrm{m\,s^{-1}}} = 8764\,\mathrm{s} = 146\,\mathrm{min} = 2.43\text{ hours}$$

12 a Apply Snell's Law

$$\frac{\sin i}{\sin r} = \frac{n_2}{n_1}$$

Rearrange for the required sin r

$$\sin r = \sin i \times \frac{n_1}{n_2}$$

Insert known values

$$\sin r = \sin 30° \times \frac{1.00}{1.49}$$

Calculate the answer

$$r = 20°$$

b The angle of refraction will get larger.

Apply Snell's Law

$$\frac{\sin i}{\sin r} = \frac{n_2}{n_1}$$

Rearrange for the required sin r

$$\sin r = \sin i \times \frac{n_1}{n_2}$$

Insert known values

$$\sin r = \sin 30° \times \frac{1.28}{1.49}$$

Calculate the answer

$$r = 25°$$

13 Apply the destructive interference formula

$$\text{path difference} = (2n - 1)\frac{\lambda}{2}$$

Insert known values

$$\text{path difference} = (2 \times 1 - 1)\frac{456 \times 10^{-9}\,\mathrm{m}}{2}$$

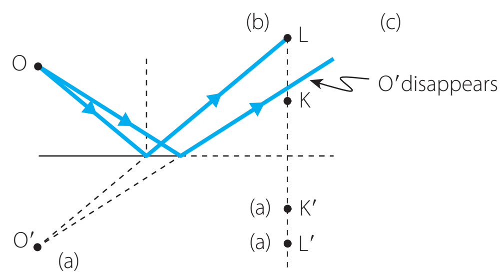
Calculate the answer

$$\text{path difference} = 228\,\mathrm{nm}$$

14 When sunlight passes into raindrops on a day when there is moisture in the air, the light undergoes chromatic dispersion as it enters the raindrop. When it is travelling in the raindrop, it will reflect off the back wall of the drop and undergo further chromatic dispersion as it is transmitted back into the air. A person will see different colours at different angles and this is why a rainbow appears circular; all of the same wavelengths have the same angle made by the path taken from the Sun to the raindrop and to the eye.

15 As the light passes through each of the double slits, it undergoes diffraction. As a result, each slit acts as a source of circular waves. These two waves can now overlap and interfere according to the principle of superposition, creating positions with constructive interference (bright spots) and areas with destructive interference (dark spots). The pattern of this interference as it strikes the screen is what is observed.

16 a



b At a point between L and K the image of O disappears.

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UNITS 1 & 2 PRACTICE EXAM ANSWERS

MULTIPLE-CHOICE QUESTIONS

1 C
2 D
3 A
4 D
5 D
6 C
7 A
8 C
9 D
10 C
11 D
12 C
13 A
14 C
15 B
16 D
17 D
18 A
19 C
20 B

SHORT-RESPONSE QUESTIONS

1 Specific heat capacity
2 3.6×10^4 J
3 ${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}X + {}^{4}_{2}He$
4 45.86 hours
5 Conventional current
6 The heat added is all going into internal energy changes but not linear kinetic energy changes.
7 The mass of the substance remains constant; the substance does not change phase; the source transfers energy at a constant rate.
8 A tightly bonded collection of positively charged protons and neutrons with no charge within the nucleus, which are surrounded by a cloud of small negatively charged electrons.
9 ${}^{235}_{92}U \rightarrow {}^{141}_{56}Ba + {}^{94}_{36}Kr$
10 150 mA; Kirchhoff's current law
11 $a = \frac{v-u}{t}$; $v^2 = u^2 + 2as$; $v = u + at$; $s = ut + \frac{1}{2}at^2$
12 87.5 N
13 $k = 85.71\ N\,m^{-1}$
14 1.72 N s
15 $44.4\ W\,m^{-2}$
16 9.96 km
17 0.14 s
18 Particles within longitudinal waves vibrate parallel with the direction of the wave. Sound waves are an example of a longitudinal wave. Particles within transverse waves vibrate perpendicular with the direction of the wave. Water waves and light waves are examples of transverse waves.
19 f = 527.1 Hz
20 Real, inverted and magnified

COMBINATION-RESPONSE QUESTIONS

1 100 kJ; 678 kJ; total heat energy 778 kJ
2 589.5°C
3 3.13×10^{-29} kg
4 360 Ω
5 I = 0.033 A
6 25.1 N
7 a $24\,000\ kg\,m\,s^{-1}$ east (car); $55\,000\ kg\,m\,s^{-1}$ west (truck)
b $31\,000\ kg\,m\,s^{-1}$ west
c $4.37\ m\,s^{-1}$
8 1.44 m
9 $\theta_r = 18.8°$
10 13.33 cm

GLOSSARY

A

absolute refractive index a measure of the refrangibility of a medium placed in a vacuum and subjected to an incident ray of light

absolute uncertainty the size of the range of values in which the true value of a measurement probably lies

absolute zero the theoretical lowest possible temperature; −273.15°C on the Celsius scale or 0 K on the absolute or Kelvin scale

acceleration time rate of change of velocity (vector); magnitude of time rate of change of velocity (scalar); time rate of change of speed (scalar)

accepted value the value of a substance or quantity that is universally agreed as being a best estimate due to multiple and highly accurate measurements

accurate the degree to which a measurement correctly reflects or approaches the true value

action-at-a-distance the application of a non-contact force

activity a measure of the magnitude of radioactive emissions. Activity is simply the number of emissions per second, measured in the SI unit Bq

alpha particle a particle containing two neutrons and two protons; a helium nucleus

alternating current (AC) current that changes direction periodically, typically 50 oscillations per second (50 hertz)

amplitude the maximum displacement of a particle in a wave from its mean position; units: m

analyser material that allows or stops polarised electromagnetic radiation

angle of incidence the angle made between an incident (incoming) wave and a normal drawn to the surface at the point of incidence

angle of reflection the angle made between a reflected wave and a normal drawn to the surface at the point of incidence

angle of refraction the angle that the refracted ray makes with the normal

anthropogenic human-derived; caused by human activity

antineutrino a very small particle that accompanies β^- decay

antinode point along a standing wave at which the wave has maximum amplitude; it is the result of a crest overlapping a crest or a trough overlapping a trough

apparent position the position that an object appears to an observer, which may be different from its actual position due to the refraction of its light waves

artificial transmutation the conversion of one chemical element or isotope into another through a synthetic process, typically through bombarding a nucleus with slow (thermal) neutrons to cause fission events

atmosphere unit of pressure; 1 atmosphere is the standard pressure found at the surface of Earth

atmospheric refraction the refraction of light rays as they pass through Earth's atmosphere

atom particle; originally thought to be indivisible, but now known to comprise numerous smaller particles

atomic mass number (*A*) total number of protons *and* neutrons in a nucleus

atomic model a series of descriptions relating to the fundamental structure of matter

atomic number (*Z*) number of protons in a nucleus

atomic weight (relative atomic mass) used interchangeably with relative atomic mass, atomic weight is the weighted average of all the masses of the different nuclides in a pure, naturally occurrence sample of the element

average speed the one (constant) speed that would allow a particle to cover the total of the various distances of a journey in a given time interval

B

body waves seismic waves that travel through the body of Earth

boiling point the temperature at which a substance undergoes a phase change from liquid to gas (vaporises)

Boltzmann distribution a formula showing the distribution of energy among the particles of a system

bombarding radiation radiation composed of particles, such as alpha particles or neutrons, that are bombarded at the nucleus to force transmutation and radioactive decay

boson a particle with integer spin s = 0 or 1. These particles do not obey the exclusion principle

Brownian motion the random motion of small objects suspended in a fluid as a result of the objects being bombarded by the particles of the fluid

C

calorie the amount of heat energy required to raise the temperature of 1 g of water by 1°C; 1 cal = 4.186 J

calorimeter a highly insulated container that prevents heat energy being lost to the environment

centre of mass the point in an extended particle where all the mass can be considered to be concentrated

chromatic dispersion occurs because different colours refract by different amounts in the same medium; colours spread

circuit breaker electromechanical switch that trips when there is an overload; safety protection against overload

cladding outer glass of an optical fibre

closed pipe a pipe that is open at one end and closed at the other end

closed system a system that can lose energy but not mass to its surroundings

collision interaction between two objects subject to action–reaction pairs of forces

combination circuit circuits that contain both series and parallel components

compression a region of high pressure in a mechanical wave

condensation the phase change from gas to liquid

condenser a vessel that removes heat from steam by allowing it to turn back to water

conduction the process by which energy is transferred through the collision of atoms

conductor a material of low resistance that allows the flow of electrons; e.g. metals

confidence interval a range of values in which an indication value lies

constructive interference the interference of in-phase waves resulting in an increased displacement at the point of overlap

contact force force applied by one object on another when they are separated by such a small distance that they appear to be touching

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continuous wave repeating waves passing through a medium

controlled chain reaction a chain of nuclear reactions that are controlled to limit the rate at which reactions occur. In steady state (reaction rate held constant), an average of one neutron from each reaction goes on to cause another reaction. This is the case for a nuclear power reactor running at constant power output

convection process by which energy is transferred through the bulk motion of a fluid

convection cell the condition that occurs when there are density differences within a fluid; the density differences result in rising and falling currents

conventional current the convention to describe electrical current as the flow of positive charge

convection current fluid circulating as a result of heating at a point or localised region; movement of fluids due to convection

converging (convex) lens lens thicker in the middle than at the end

coplanar in the same plane

core inner glass of optical fibre

Coulomb's law describes the force of attraction or repulsion between two charges, separated by some distance

crest the positive peak of a wave; units: m

critical angle angle of incidence for which the angle of refraction is 90° (total internal reflection occurs); beyond the critical angle, reflection but no refraction occurs

current, *I* the rate of flow of charge; that is, charge per unit time. It is measured in amperes, A: $I = \frac{q}{t}$

D

daughter nuclide the nuclide formed after a parent nuclide has emitted particles from its nucleus; the daughter nuclide is more stable than the parent nuclide

decay the decrease in amplitude when the vibrating source of a wave is removed

deceleration negative acceleration

delocalised valence electrons the outer electrons of metal atoms that are free to move

dependent variable the variable that changes as a result of a change in the independent or controlled variable

deposition the phase change from gas to solid without becoming a liquid

derive to obtain or create from base principles

derived data data that are deduced from raw data by mathematical manipulation, such as graphs, algebraic equations and geometric constructions

destructive interference the interference of out-of-phase waves resulting in a decreased displacement at the point of overlap

diffraction the bending of waves around an obstacle

diffuse reflection (scattering) reflection from a rough surface rays in a beam reflect in different directions

diffusion the spontaneous movement of substances of energies from areas of high concentration to areas of low concentration

direct current (DC) current that is always in one direction

displacement position relative to another position; the difference between two positions specified with respect to an origin; the straight-line distance between the current position of a particle in a wave and its mean position

distance length

diverging (concave) lens lens that is thicker at the edges than in the middle

Doppler effect the shift in the wavelength and frequency of waves that results from the relative motion of the source and the receiver

driving frequency the vibration of an object that causes a second object to undergo resonance

E

elastic collision a collision between two or more objects in which there is no loss of kinetic energy

elastic potential energy energy stored in a spring system; energy that is stored by the deformation of an elastic object

electrical circuit a complete conducting loop through which charge can flow

electromagnetic force the combined electrical and magnetic force acting between charged particles; the force is attractive for unlike charges, and repulsive for like charges

electromagnetic radiation energy that travels as waves and moves at the speed of light

electromagnetic spectrum the continuous spectrum describing all radiation from high energy to low energy

electromagnetic wave model light acts like a transverse wave that has electric and magnetic components

electromotive force, EMF source of potential energy per charge (voltage)

electron a negatively charged subatomic particle and the primary charge carrier in conductors; $q_e = -1.60 \times 10^{-19}$ C; mass 9.11×10^{-31} kg

electron-volt, eV a small energy unit, equivalent to 1.60×10^{-19} J

element a substance that only has atoms with the same number of protons

EMF electromotive force; source of potential energy per charge. Measured in volts, V

energy a fundamental quantity that can be transformed and transferred; it is defined by source or by the way it is measured

energy change energy transfer or transformation; quantity of energy that can be measured

energy efficiency the fraction of input energy that is converted in a thermodynamic process to useful output energy

enrichment a process of separating out U-235 from a sample and adding it to another sample, increasing the proportion of U-235 in natural uranium

epicentre the point on the Earth's surface directly above the seismic focus

evaporation the process in which some of the particles with high kinetic energy escape the surface of a liquid at a temperature below its boiling point

external combustion engine a device to produce work through the expansion of a fluid that is heated by the combustion of an external fuel source

extrapolation extension beyond the measured range of data to read or construct a new data point that has not been measured

F

first harmonic the simplest mode of vibration that accounts for the fundamental tone

first law of thermodynamics in the universe, energy can neither be created nor destroyed; however, energy can change forms and energy can flow from one place to another. The total energy of an isolated system remains constant

fissile capable of being split or divided, e.g. by undergoing fission; U-235, U-238, U-233, Pu-239

fission the process by which heavy nuclei ($Z > 56$) separate into fragments, with the release of energy; typically, fission fragments have quite different masses

fission fragment nucleus produced as a result of fission; fission product

focal length distance from lens to focal point

focal point the point to which light which is parallel to the axis of a lens is focused

forced vibration the vibration that occurs in an object when it is forced to vibrate by another vibrating object

frame of reference system within which measurements are made; point of view

frequency (f) the number of whole waves of cycles in one second; units: Hz

friction force force applied by a surface parallel to the surface

fuse temperature dependent wire that melts if an overload occurs; safety protection against overload

fusion the process by which nucleons join to form a new nucleus. Nucleosynthesis is the set of fusion reactions that lead from nucleons to a variety of nuclides. This occurs for light elements ($Z < 56$) and energy is released

G

gamma rays high-energy electromagnetic radiation

gravitational force the manifestation of Newton's universal law of gravitation; a force of attraction acting between every mass throughout the universe

gravitational mass mass of an object that acts at a distance on other masses via gravitational force

gravitational potential energy energy stored in a system comprising masses subject to gravitational force

gravity gravitational force applied by Earth's mass on smaller masses on or near Earth; by extension, the force applied by a large celestial mass, such as a moon or a planet, on nearby masses

ground energy state the state in which a nucleus has absorbed no energy, and requires no additional energy to maintain its state

H

half-life the time it takes for half of a radioactive substance to decay

heat conductor a material that readily allows the transfer of heat

heat engine a system that converts heat energy to work

heat insulator a material that is a poor conductor of heat

heat pump system that moves thermal energy from one place to another

heat sink an object or material that moderates the temperature of its surroundings due to its large specific heat capacity

heat the transfer of thermal energy through a substance or between substances

heat-conversion system a system that transforms the internal energy of a system

heat-exchange system any system that transfers heat from a warmer to a cooler place

heating curve a plot of temperature versus time or heat added

I

ideal gas a theoretical gas whose particles have no attraction to or repulsion from each other

image picture of an object

impulse action of a force over a time interval; $\vec{J} = \vec{F}t$

in phase when two waves of equal wavelength have their crests and troughs aligned

incident wave incoming wave

independent variable a variable upon which another variable is dependent; also called the controlled variable

indication value single result of a measurement

inertia, inertial mass tendency of a body to continue in its state of rest or of uniform motion in a straight line

instantaneous time a particular moment on a clock

insulator a material that inhibits the flow of electrons, e.g. rubber

intensity a measure of the energy per unit time travelling through a unit area perpendicular to the direction of travel

interference wave overlap

interferometer an instrument that uses wave interference to make precise measurements of the distance travelled by waves in terms of their wavelength

intermolecular forces electrostatic forces of attraction or repulsion between neighbouring particles of a substance

internal energy the sum of the kinetic energy of the particles in a system and the potential energy stored in a system

interpolation to read or construct a new data point that has not been measured but is within the range of measured data

interval change in a quantity such as time interval, displacement interval, velocity interval

ionising power the ability to ionise nearby atoms; high ionising power means it is likely for nearby atoms to have their electrons stripped

ionising radiation electromagnetic radiation that does ionise nearby atoms and has high energy

isolated system system that no matter or energy transfers into or out of and in which no energy is created or destroyed inside

isotopes elements with the same number of protons, but a different number of neutrons in the nucleus

J

joule SI unit of energy; $1\,\text{J} = 1\,\text{kg}\,\text{m}^2\,\text{s}^{-2}$

K

kilowatt hour (kWh) a convenient measure of electrical energy equal to the power consumption of one kilowatt over a period of one hour: $1.0\,\text{kWh} = 3.6 \times 10^6\,\text{J}$

kinetic energy the energy of an object due to its motion

kinetic particle model the model that explains the properties of the different states of matter; the particles in solids, liquids and gasses have different amounts of energy, are arranged differently and move in different ways

Kirchhoff's current law (first law) the total current arriving at a junction within an electrical circuit is equal to the total current leaving the junction

Kirchhoff's voltage law (second law) for any closed loop in an electrical circuit, the sum of the potential differences must be zero

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L

latent heat the heat required to change the state of a substance at its boiling point or melting point without a change in temperature; unit: J kg^{-1}

law of conservation of charge the net charge within an isolated system is constant

law of reflection when a wave is incident upon a surface, the angle of reflection is equal to the angle of incidence

linearise to make linear; to convert to a form that can be described by a straight line

longitudinal wave a wave whose particles oscillate about a mean position in the same line as the direction of travel of the wave

luminous a source that produces light

luminous aether a non-existent substance that was proposed to exist in early wave models of light as the medium through which light could travel

M

magnification (*M*) ratio of image height to object height

mass defect, Δm the difference in the mass of an atom and the mass of its constituent parts, as expressed in Einstein's mass–energy equation: $E = mc^2$

matter a physical substance

maximum value upper limit of a confidence interval

mean value the average value of a set of indication values

measurand a specified quantity to be measured

measurement result the best estimate of the 'true value' of a measurand given the limitations of the actual measurement device used

mechanical waves waves that require a physical substance to be able to propagate

medium a substance that allows the transfer of energy from one place to another

melting the phase change from solid to liquid

melting point the temperature at which a substance undergoes a phase change from solid to liquid (melts)

metallic lattice a regular arrangement of large numbers of metal atoms that allows free electrons to move readily

metastable a nuclide is metastable if it can remain in a higher energy state for a certain period of time

minimum value lower limit of a confidence interval

moderator light atoms in a nuclear reactor that slow down fast neutrons to thermal speeds, in order to increase the likelihood of further fission events; often heavy water is used

molecule a collection of atoms bound together by chemical bonds

momentum quantity of motion calculated by the product of mass and velocity; $\vec{p} = m\vec{v}$

N

natural (or free) frequency the vibration frequency that occurs when an object is displaced from its equilibrium position and then left to vibrate by itself

natural transmutation the conversion of one chemical element or isotope into another through natural radioactive decay

negligible so small it can be ignored; very little

neutrino a very small particle that accompanies β^+ decay

neutron a neutrally charged subatomic particle within the nucleus of an atom. The mass of a neutron is approximately the same as that of a proton

node point along a standing wave at which the amplitude is zero; it is the result of a crest overlapping a trough

non-contact force force applied by one object on another when they are separated by distance

non-ionising radiation electromagnetic radiation that does not ionise nearby atoms and has low energy

non-luminous a source that reflects light

non-ohmic device a component that does not provide a constant resistance: $R \neq \frac{V}{I}$

normal a line drawn perpendicular to a surface

normal force force applied by surface at right angles (normal) to the surface

nuclear binding energy energy needed to disassemble a nucleus into its component nucleons; measure of stability of a nuclide

nucleon a proton or neutron; a particle that makes up the nucleus of an atom

nucleus centre of an atom that comprises the majority of an atom's mass

nuclides elements with the same number of protons and neutrons with the nucleus in the same energy state of nuclides. This occurs for light elements ($Z < 56$) and energy is released

O

Ohm's law the physical law that relates the current that flows through a conductor as directly proportional to the voltage across the conductor; that is, $\frac{V}{R}$ = a constant. The constant is termed the resistance of the conductor

ohmic device a component with constant resistance, i.e. a device that exhibits a proportional relationship between current and voltage: $R = \frac{V}{I}$

opaque not transparent; not able to be seen through

open pipe a pipe that is open at both ends

open system a system that can lose mass and energy to its surroundings

optical centre centre of curvature of a lens

optical fibre transparent light guide making use of total internal reflection at a boundary between materials of similar refractive index

out of phase when the crests of a wave align with the troughs of another wave of equal wavelength

P

P wave longitudinal earthquake compression waves that pass through the body of Earth

parallax error error in a measurement caused by the change in the apparent position of an object viewed from two different lines of sight

parallel circuit a circuit with multiple paths through which current can flow

parent nuclide the original nuclide before emitting particles from the nucleus

penetrating power the ability to penetrate air, liquids and solids; radiation with high penetrating power can penetrate highly compacted solids

percentage error the difference between a measurement result and an accepted value, expressed as a percentage of the accepted value

percentage uncertainty a measure of the uncertainty of a measurement compared with the size of the measurement, given as a percentage

period (*T*) the time it takes before a wave repeats itself; units: s

phase change a change in physical state (e.g. solid to liquid)

photon a particle of light

Planck radiation curve a formula that describes the relationship between the electromagnetic radiation emitted by a substance and its temperature

plane mirror a mirror with a plane (flat) reflecting surface

plasma a collection of freemoving electrons and ions that can be accelerated by magnetic and electric fields

point source single localised source from light transmits equally in all directions

polarisation orientation in one direction of the electrical part of electromagnetic waves

polariser material that selects the direction of polarisation

potential difference, *V* a measure of the potential energy per unit of charge. Potential difference and voltage are measured in volts (V); also termed voltage: $V = \frac{W}{q}$

potential energy energy that is stored in a system due to the configuration and interaction of the bodies within the system; energy available to do work

power, *P* a measure of the rate of energy transformation per unit of time. It is measured in watts, W

precise the degree to which the individual measurements cluster around their mean value

principal axis line through both focus and centre and perpendicular to the axis of a curved lens

principle of superposition when two or more waves of the same nature travel past a point in a medium, the medium will undergo a resultant displacement at that point, which is the sum of the individual particle displacements due to the waves at that point

proportional error the difference between a measurement result and an accepted value, expressed as a fraction of the accepted value

proton a positively charged subatomic particle found within the atomic nucleus; $q_p = 1.60 \times 10^{-19}$ C

pulse a single wavefront travelling through a medium

Q

qualitative non-numerical data; descriptive information

quantitative numerical data; specific amount

R

radiation energy transfer across space; the process by which heat is transferred without the need for a medium; energy from radioactive atoms

radioactive decay also called nuclear transformation, disintegration and transmutation; occurs when particles are emitted from the nucleus of an atom, causing it to change into a new nuclide. It can happen naturally or be forced by impact from subatomic particles outside the nucleus

radioactivity particles or rays that come from energy rearrangements in a nucleus

random error a variation that affects a measurement in a random way so that successive measured values may reflect small changes from each other; also known as a two-sided error, presents as values above and below the expected values

range the difference between the maximum and minimum values of a measured confidence interval

rarefaction a region of low pressure in a mechanical wave

raw data original data taken directly from a measurement system

ray a line drawn at right angles to a wavefront and in the direction of travel

ray diagram a diagram that traces the path taken by light in order for a person to view an object

ray model a model that describes light as travelling in rays that change direction during interactions with matter

real image image of an object where the rays of the image do not pass through the image itself; the image can be projected onto a screen

refraction the change in direction of a wave when it strikes a surface at an angle other than 90°. The speed and wavelength of the wave also change; frequency remains constant

refractive index measure of refrangibility; measure of the relative change of direction of waves or light rays when travelling from one medium to another

refrangibility a measure of how much refraction will occur when light moves into a particular material from a vacuum

regular or specular reflection predictable reflection from a very smooth surface; rays in a beam all reflect in the same direction

relative refractive index the comparative difference in refrangibility between two media with different absolute refractive indices

relative uncertainty a measure of the uncertainty of a measurement as a fraction of the measurement result

residual current device (RCD) earth-leakage protection device; safety protection against overload

resistance the opposition to the flow of electrical charge throughout a given material; it is measured in ohms, Ω, and is the ratio between potential difference and current

resistivity, ρ a measure of how much a material opposes the flow of charges; resistivity has the units Ω m

resonance when an object is made to oscillate at its natural frequency by the vibration of another object that is also vibrating at that natural frequency

resonant frequencies the possible standing wave frequencies of an object

reverberation the effect that occurs when too many sound wave reflections arrive at your ear for you to distinguish between the sounds

root mean square voltage (V_{rms}) AC voltages may be compared to DC voltages by converting the peak voltage to the root mean square voltage, or V_{rms}:V_{peak}

S

S (or shear) wave transverse earthquake waves that shake Earth in directions which are perpendicular to the direction that the wave is travelling; also known as shear waves

scalar quantity specified by one measurement scale only, such as magnitude

second law of thermodynamics the direction of heat flow is always from a hotter object to a colder object

seismic focus the underground point from which earthquake energy is released

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seismograph a device that records the amplitude and frequency of seismic waves and yields information about Earth and its subsurface structure

semiconductor a material that conducts electricity less readily than a conductor but more than an insulator

series circuit a circuit with only one path through which the charge can flow

short circuit connection between two points that allows current to flow with negligible resistance

SI system the modern form of the metric system that stipulates the true values of units

significant figure digit reported in a measurement result; the number of significant figures is the number of meaningful digits in a measurement result

sinusoidal pattern a pattern that is similar in shape to that of a sine wave

slow (thermal) neutron neutron with kinetic energy of about 0.1–20 keV

solidification the phase change from liquid to solid

specific heat capacity the amount of energy required to increase the temperature of 1 kg by 1°C (or Kelvin) of a substance without a change of phase; Unit: $J\,kg^{-1}\,K^{-1}$ or $J\,kg^{-1}\,°C^{-1}$

specific latent heat of fusion the heat required to change the state of 1 kg of a substance from a solid to a liquid without a change in temperature

specific latent heat of vaporisation the heat required to change the state of 1 kg of a substance from a liquid to a gas without a change in temperature

speed time rate of change of distance; magnitude of velocity (scalar)

spontaneously happening without any external action; all radioactive materials decay spontaneously, in a random and unpredictable way, and it is impossible to predict when one atom will decay, if at all in a given time period

standing wave (stationary wave) a wave that oscillates in place, without transmitting energy along its extent. Standing waves have stable points called nodes, where there is no oscillation

static electricity charges at rest, or stationary; typically produced on insulators by friction between two surfaces

strong nuclear force the force required to hold nucleons together, especially to overcome the electrostatic force of repulsion between protons

subatomic particles particles within an atom

sublimation the phase change from solid to gas without becoming a liquid

superheated steam steam that is held under high pressure and heated to a temperature above the boiling point of water

system any object or set of objects under investigation

systematic error also known as a one-sided error, presents as values that are either consistently above or consistently below expected values; an error that acts in a predictable manner to give a consistent offset in data

T

temperature a measurement of the average kinetic energy of the particles in a substance

thermal conductivity a measure of how efficiently heat can be conducted through a material

thermal currents rising air columns of hotter air caused by the process of convection

thermal energy heat, the form of energy that gives rise to an increase in the kinetic energy of particles

thermal equilibrium the condition in which two or more objects in physical contact have the same temperature and average kinetic energy as each other

thermistor temperature-dependent resistor; used to detect changes in temperature

thermometer a device that measures temperature or a temperature gradient

time interval time between two measurements of time

total internal reflection the transport and containment of a wave by coherently reflecting it back and forth in a tube

transmutation the conversion of one chemical element into another as the result of a nuclear reaction, such as neutron capture, or occur spontaneous radioactive decay, such as alpha decay and beta decay

transuranic element an element that can only be produced synthetically, and does not exist naturally in the universe

transverse wave a wave whose particles oscillate about a mean position perpendicular to the direction of travel by the wave

trough the negative peak of a wave; units: m

true value for continuous variables, this is an unknowable, ideal value that represents the measurand

U

uncertainty estimate of the range of values within which the true value of a measurement or derived quantity lies

uncontrolled chain reaction a chain of nuclear reactions that are not controlled. Usually this means a reaction rate that increases rapidly. For this to occur the average number of neutrons from each reaction that go on to cause more reactions is greater than one

unstable describes a nucleus that is likely to decay because the strong nuclear force is not large enough to overcome the electrostatic repulsion force

usable energy energy that can be used to perform some desired result; usually in the form of energy to do work

V

vaporisation the phase change from liquid to gas

vector quantity that has magnitude and direction; quantity characterised by two or more scales (from Greek 'to convey')

velocity time rate of change of displacement; speed with direction (vector)

vibration mode or harmonic standing wave pattern

virtual image image of an object where the rays do not pass through the image; the image cannot be projected onto a screen

voltage divider device used to vary voltage at the output depending on a control resistor; also called a potential divider

W

watt (W) the unit of power; $1\,W = 1\,J\,s^{-1}$

wave model a model of that describes light as travelling as waves

wave velocity the velocity at which crest move through a medium

wavefront an imaginary surface joining all points in space that are reached at the same instant by a wave propagating through a medium

wavelength (λ) the distance travelled by a wave before it repeats itself; units: m

wave–particle duality the need to model light as both a wave and a particle

weak nuclear force one of the four fundamental forces; acts between subatomic particles (leptons) and is responsible for beta decay

weight gravitational force on mass; force exerted by mass of Earth on masses 'near Earth'; by extension, force by any large mass in the universe, such as the Moon, on any smaller mass 'nearby'

work force acting over a distance interval; the energy transferred due to the action of a force over a distance

Z

zeroth law of thermodynamics if two systems are in thermal equilibrium with a third system, then they must be in thermal equilibrium with each other

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Periodic table of elements

IUPAC with minor modifications for teaching purposes

Key

atomic number → 26
Fe (Symbol of element)
name of element → iron
atomic weight → 55.85

Symbol of element:
- gas at room temperature (red)
- liquid at room temperature (green)
- solid at room temperature (black)
- synthetic (does not occur naturally) (blue)

- s block
- p block
- d block transition metals
- d block lanthanoids and actinoids

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H hydrogen 1.008																	2 He helium 4.003
3 Li lithium 6.941	4 Be beryllium 9.012											5 B boron 10.81	6 C carbon 12.01	7 N nitrogen 14.01	8 O oxygen 16.00	9 F fluorine 19.00	10 Ne neon 20.18
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19 K potassium 39.10	20 Ca calcium 40.08	21 Sc scandium 44.96	22 Ti titanium 47.87	23 V vanadium 50.94	24 Cr chromium 52.00	25 Mn manganese 54.94	26 Fe iron 55.85	27 Co cobalt 58.93	28 Ni nickel 58.69	29 Cu copper 63.55	30 Zn zinc 65.38	31 Ga gallium 69.72	32 Ge germanium 72.63	33 As arsenic 74.92	34 Se selenium 78.96	35 Br bromine 79.90	36 Kr krypton 83.80
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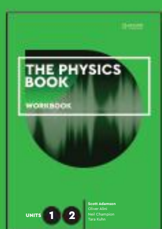

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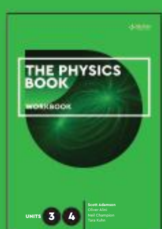

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