Marshall Cavendish Education

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Cambridge IGCSE™ Physics

STUDENT'S BOOK

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How to use this book

This book is designed to help you to build your knowledge and understanding of essential scientific concepts. It will also enable you to appreciate the application of Physics in your everyday life and in the world around you. This Student's Book is part of the Marshall Cavendish Education suite of resources that will support you as you follow the 0625/0972 syllabus and prepare for the Cambridge IGCSE Physics.


CHAPTER 4

Forces

Low res image

PHYSICS WATCH

Scan this page to watch a clip what keeps a kite flying in the air.

QUESTIONS

- A main force is responsible to enable the *wau bulan* to fly. Where does this force come from?
- What other forces are acting on the kite when it is flying in the air?
- A big *wau bulan* will not fly when the wind is not strong enough. Why?

This man is getting ready to fly his *wau bulan*. *Wau bulan* is a type of kite traditionally flown in Kelantan, a state in Malaysia. The lower part of the kite is shaped like a crescent moon. That is how the kite got its name — *bulan* means *moon* in Malay.

A typical *wau bulan* measures 2.5 m in width and 3.5 m in height. Its frame is made of bamboo. A large *wau bulan* can be very heavy and would need several people to launch it into the sky. When there is a strong wind, the *wau bulan* is lifted up. The forces acting on it enable it to fly as high as 500 m in the air. To control the height and path of the kite, a few people on the ground hold and pull the string attached to it.

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***Chapter opener** introduces the topic and links concepts to real-life examples.

PHYSICS WATCH*

provides multimedia resources, such as videos, animations and simulations, making learning 'come alive'. The resources can be called out on a smartphone or a tablet by scanning a page using the ***MCE Cambridge IGCSE App***.

QUESTIONS*

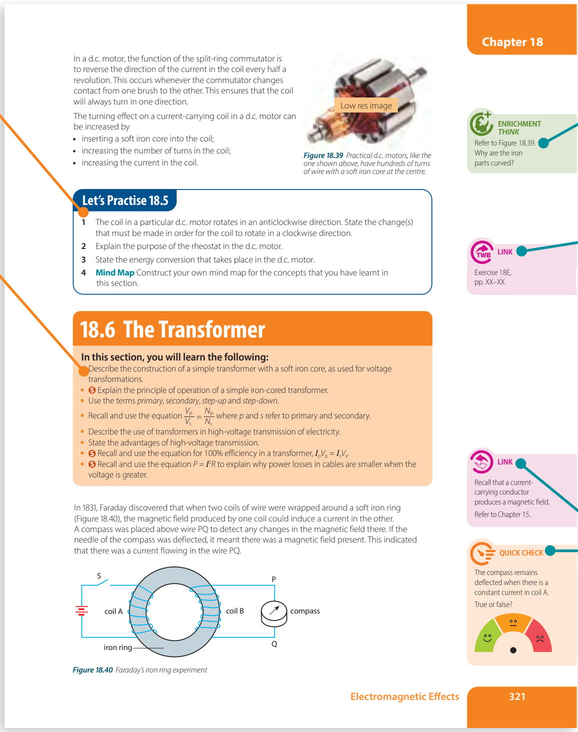
assesses your prior knowledge on the topic.

Let's Practise provides formative assessment questions at the end of sections to test your ability to recall and apply concepts learnt.

Learning goals help you identify areas of focus and serve as a checklist.

QUICK CHECK

serves as a checkpoint to check your understanding of concepts by posing a true or false question. Rate your confidence level in your answer by drawing a pointer on the confidence meter. Relating your answer and confidence level to the correct answer helps you to detect any lack of knowledge or potential misconceptions. For example, "High confidence in an incorrect answer would suggest a misconception" and "low confidence in a correct answer would suggest a lack of knowledge".


Chapter 18

In a d.c. motor, the function of the split-ring commutator is to reverse the direction of the current in the coil every half a revolution. This occurs whenever the commutator changes contact from one brush to the other. This ensures that the coil will always turn in one direction.

The turning effect on a current-carrying coil in a d.c. motor can be increased by

- inserting a soft iron core into the coil;
- increasing the number of turns in the coil;
- increasing the current in the coil.

Low res image

Figure 18.39 Practical d.c. motors, like the one shown above, have hundreds of turns of wire with a soft iron core at the centre.

ENRICHMENT THINK

Refer to Figure 18.39. Why are the iron parts curved?

Let's Practise 18.5

1 The coil in a particular d.c. motor rotates in an anticlockwise direction. State the change(s) that must be made in order for the coil to rotate in a clockwise direction.
2 Explain the purpose of the rheostat in the d.c. motor.
3 State the energy conversion that takes place in the d.c. motor.
4 Mind Map Construct your own mind map for the concepts that you have learnt in this section.

LINK

Exercise 18E, pp. XX–XX

18.6 The Transformer

In this section, you will learn the following:

- Describe the construction of a simple transformer with a soft iron core, as used for voltage transformations.
- S Explain the principle of operation of a simple iron-cored transformer.
- Use the terms *primary*, *secondary*, *step-up* and *step-down*.
- Recall and use the equation $\frac{V_p}{V_s} = \frac{N_p}{N_s}$ where *p* and *s* refer to primary and secondary.
- Describe the use of transformers in high-voltage transmission of electricity.
- State the advantages of high-voltage transmission.
- S Recall and use the equation for 100% efficiency in a transformer, $I_pV_p = I_sV_s$.
- S Recall and use the equation $P = I^2R$ to explain why power losses in cables are smaller when the voltage is greater.

LINK

Recall that a current-carrying conductor produces a magnetic field.

Refer to Chapter 15.

In 1831, Faraday discovered that when two coils of wire were wrapped around a soft iron ring (Figure 18.40), the magnetic field produced by one coil could induce a current in the other. A compass was placed above wire PQ to detect any changes in the magnetic field there. If the needle of the compass was deflected, it meant there was a magnetic field present. This indicated that there was a current flowing in the wire PQ.

QUICK CHECK

The compass remains deflected when there is a constant current in coil A.

True or false?

S

P

coil A

coil B

compass

iron ring

Q

Figure 18.40 Faraday's iron ring experiment

Electromagnetic Effects

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ENRICHMENT THINK*

poses challenging questions that encourage you to apply the concepts learnt to various contexts and prompts higher-level critical thinking.

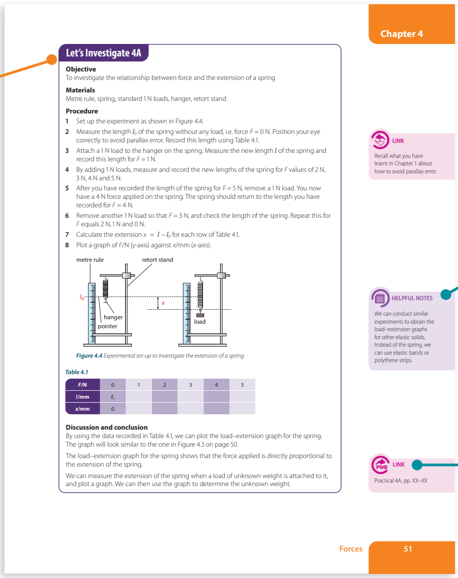
LINK

leads you to the revision exercises in the Theory Workbook.

LINK

helps you make connections between sections or chapters.

Let's Investigate introduces experimental skills and techniques, and allows you to see how concepts are formed and tested.



HELPFUL NOTES

supports your learning by providing tips, such as mnemonics, and highlighting important notes that you need to be aware of.

LINK

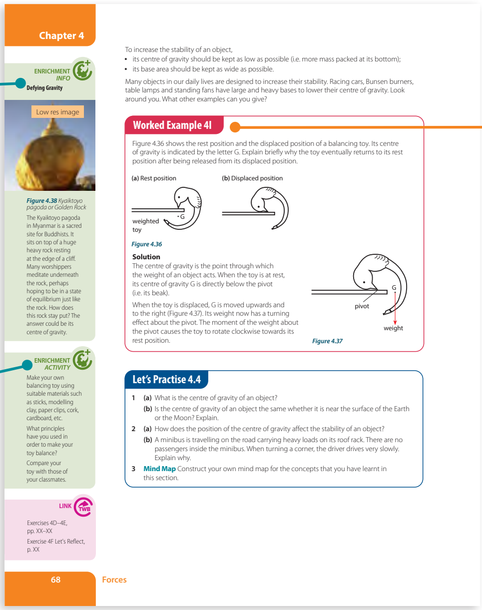
leads you to practicals in the Practical Workbook.

***ENRICHMENT INFO**

offers snippets of information to supplement your general knowledge and provide additional context related to the topic.

***ENRICHMENT ACTIVITY**

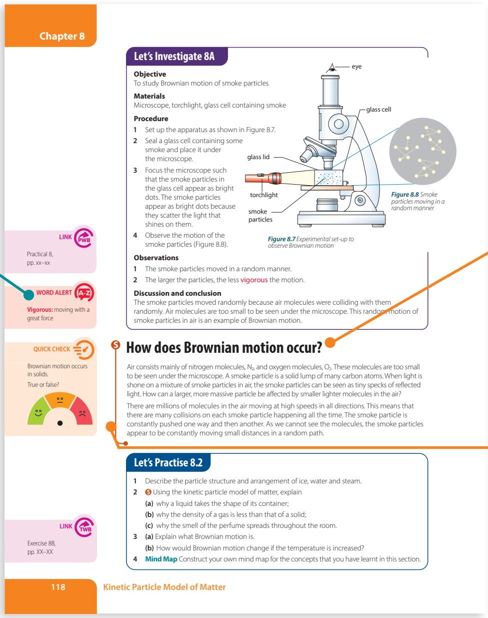
provides individual and group activities that encourage deeper thought to help reinforce your learning.



Worked Example demonstrates how to solve problems by applying concepts learnt.

WORD ALERT

provides information on words or explains words in a simpler way to help you understand their meanings in context. This also helps you to be more familiar with the words and be confident in using the words.

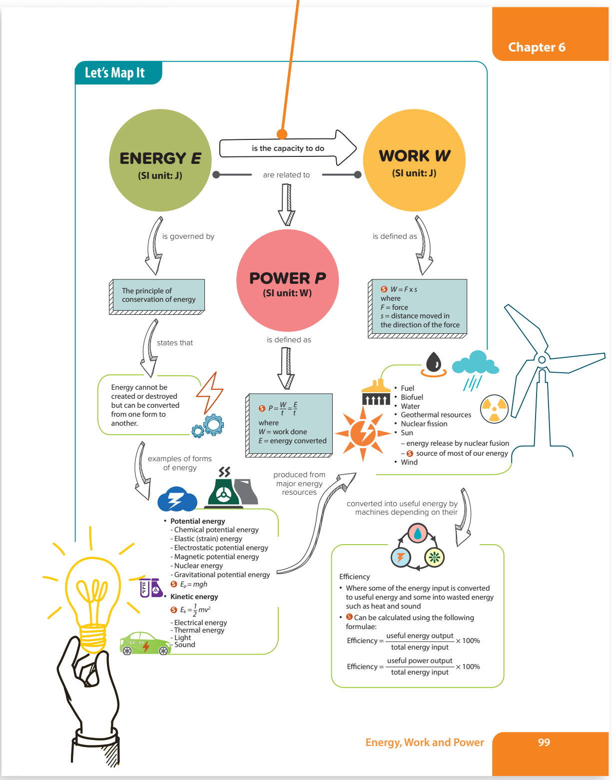


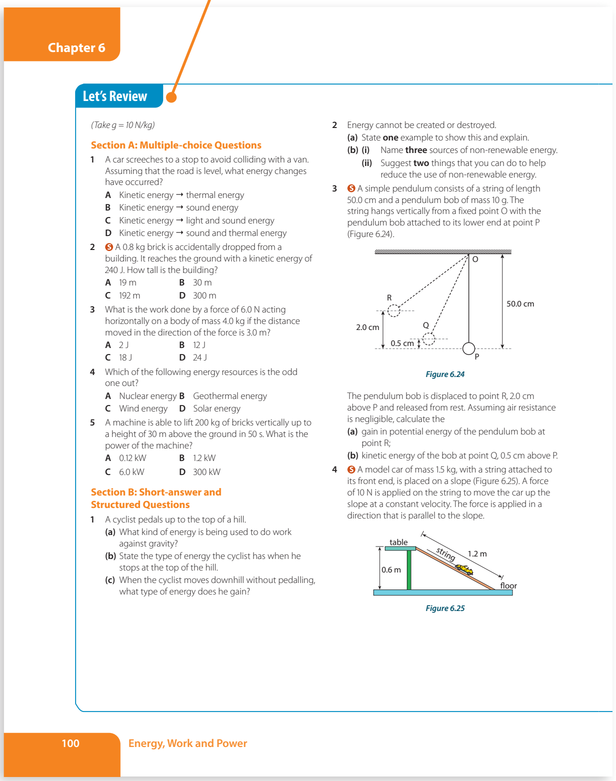
Headings are often posed as questions so that information is always directed towards helping you to answer essential questions about the topic.

Supplement content is clearly marked for those taking the Extended paper.

Let's Map It provides a visual summary of the concepts covered to help you integrate your learning and form connections between different concepts.

Let's Review offers summative assessment questions to test your understanding and gives you practice in answering exam-style questions.





Chapter 6

Let's Review

(Take g = 10 N/kg)

Section A: Multiple-choice Questions

1 A car screeches to a stop to avoid colliding with a van. Assuming that the road is level, what energy changes have occurred?
- **A** Kinetic energy → thermal energy
- **B** Kinetic energy → sound energy
- **C** Kinetic energy → light and sound energy
- **D** Kinetic energy → sound and thermal energy

2 Ⓢ A 0.8 kg brick is accidentally dropped from a building. It reaches the ground with a kinetic energy of 240 J. How tall is the building?
- **A** 19 m **B** 30 m
- **C** 192 m **D** 300 m

3 What is the work done by a force of 6.0 N acting horizontally on a body of mass 4.0 kg if the distance moved in the direction of the force is 3.0 m?
- **A** 2 J **B** 12 J
- **C** 18 J **D** 24 J

4 Which of the following energy resources is the odd one out?
- **A** Nuclear energy **B** Geothermal energy
- **C** Wind energy **D** Solar energy

5 A machine is able to lift 200 kg of bricks vertically up to a height of 30 m above the ground in 50 s. What is the power of the machine?
- **A** 0.12 kW **B** 1.2 kW
- **C** 6.0 kW **D** 300 kW

Section B: Short-answer and Structured Questions

1 A cyclist pedals up to the top of a hill.
- **(a)** What kind of energy is being used to do work against gravity?
- **(b)** State the type of energy the cyclist has when he stops at the top of the hill.
- **(c)** When the cyclist moves downhill without pedalling, what type of energy does he gain?

2 Energy cannot be created or destroyed.
- **(a)** State **one** example to show this and explain.
- **(b) (i)** Name **three** sources of non-renewable energy.
- **(ii)** Suggest **two** things that you can do to help reduce the use of non-renewable energy.

3 Ⓢ A simple pendulum consists of a string of length 50.0 cm and a pendulum bob of mass 10 g. The string hangs vertically from a fixed point O with the pendulum bob attached to its lower end at point P (Figure 6.24).

O R Q P 2.0 cm 0.5 cm 50.0 cm

Figure 6.24

The pendulum bob is displaced to point R, 2.0 cm above P and released from rest. Assuming air resistance is negligible, calculate the
- **(a)** gain in potential energy of the pendulum bob at point R;
- **(b)** kinetic energy of the bob at point Q, 0.5 cm above P.

4 Ⓢ A model car of mass 1.5 kg, with a string attached to its front end, is placed on a slope (Figure 6.25). A force of 10 N is applied on the string to move the car up the slope at a constant velocity. The force is applied in a direction that is parallel to the slope.

table string 1.2 m 0.6 m floor

Figure 6.25

100 Energy, Work and Power

The following are also included at the end of the book:

- **Notes to Physics Practical Work** – provides information on laboratory safety, some common experimental contexts in practical work, and the practical skills involved in the planning of experiments and investigations
- **Quick Revision Guide** – lists each chapter's key concepts and formulae for easy revision
- **Answers** – provided for questions in Quick Check, Let's Practise and Let's Review (only numerical and short answers are included)
- **Index** – provided to help you search for key terms and phrases in the book

Note: *Features indicated with an asterisk (*) are for enrichment and are beyond the syllabus.*

Contents

CHAPTER 1

Measurement of Physical Quantities

PHYSICS WATCH

Scan this page to watch a clip about physical measurements of a baby.

QUESTIONS

- What do you understand by the term *average*?
- Other than head circumference, what are two other important measurements taken to monitor a baby's growth pattern?
- What are some other physical quantities that are commonly used as measurements in daily life?

From the day you were born, you were being measured. You wouldn't remember, but your parents probably took you to the clinic several times to have you measured. The measurements taken were then plotted to monitor your growth pattern.

Head circumference is an important measurement to monitor during the first two years of a baby's life. The average head circumference of a newborn is about 33 cm. By monitoring the baby's head circumference, we can detect if the baby's head and the brain inside it are growing normally.

1.1 Physical Quantities

In this section, you will learn the following:

- Describe the use of rulers and measuring cylinders to find a length or a volume.
- Describe how to measure a variety of time intervals using clocks and digital timers.
- Determine an average value for a small distance and for a short interval of time by measuring multiples.

Physics is the study of our natural world — from the very large (e.g. the solar system) to the very small (e.g. the atom). The study of physics is related to two main ideas: matter and energy. The knowledge we have gained in the field of physics is the result of the work of many scientists. These scientists have conducted many experiments to verify their ideas on matter and energy. When they carry out experiments, they need to make accurate measurements in order to obtain reliable results.

What are physical quantities?

Look at the sign in Figure 1.1. You may have noticed similar signs along bridges where vehicles can pass underneath. In physics, height is a physical quantity — '3.8' is the numerical magnitude and 'm' is the unit.

A **physical quantity** is a quantity that can be measured. It consists of a numerical magnitude and a unit.

There are altogether seven basic physical quantities, or base quantities. Table 1.1 shows the seven base quantities and their corresponding SI units. **SI units** are the units of measurement in the widely used International System of Units (abbreviated SI from French: *Système International d'Unités*).

WORD ALERT

Magnitude: size

Figure 1.1 *The sign warns drivers on the clearance limit to pass underneath the bridge. In which other places can you find similar signs?*

Table 1.1 *The seven base quantities and their SI units*

Base quantity	SI unit	Symbol for SI unit
Length	metre	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Luminous intensity	candela	cd
Amount of substance	mole	mol

ENRICHMENT INFO

Do you know?

1. The length from your wrist to your elbow is the same as the length of your foot.
2. Your mouth produces 1 *l* of saliva a day.
3. Breathing generates about 0.6 g of carbon dioxide every minute.
4. On average, people can hold their breath for about one minute. The world record is 21 min 29 s.

Other common physical quantities such as area, volume and speed are derived from the seven base quantities. They are called *derived quantities*. For example, speed is derived from length (i.e. distance travelled) and time. Table 1.2 gives examples of how some common physical quantities are derived from the base quantities.

Table 1.2 *Some common derived quantities and their SI units*

Physical quantity	How it is derived from base quantities	Symbol for SI unit
Area	Length × width	m^2
Volume	Length × width × height	m^3
Speed	$\frac{\text{Length}}{\text{Time}}$	m/s

PHYSICS WATCH

Scan this page to watch a clip about how unit errors can cause a disaster.

In the past, people used parts of their bodies and things around them as units of measurement. That was how measuring terms such as the foot, yard and horsepower came about. Unfortunately, such methods of measurement created much confusion because the measurement varied from individual to individual. It was not until 1968 that scientists agreed to adopt one universal set of units — the SI units.

Prefixes for SI units

Using decimal notation, the distance between air molecules can be expressed as 0.000 000 01 m. If we need to mention this quantity a number of times, it would be tedious to use this type of notation. Instead of using decimal notation, it is more convenient to use prefixes to represent the quantity. For example, when measuring short distances such as $\frac{1}{1\,000\,000}$ of a metre, we simply express it as one micrometre.

Thus, 0.000 000 01 m can be expressed as 0.01 μm (micrometre), where μ represents the submultiple 10^{-6}. The prefixes listed in Table 1.3 are useful for expressing physical quantities that are either very big or very small.

Table 1.3 *Some common prefixes and their symbols*

	Factor	Prefix	Symbol
Multiples	10^9	giga-	G
	10^6	mega-	M
	10^3	kilo-	k
Submultiples	10^{-1}	deci-	d
	10^{-2}	centi-	c
	10^{-3}	milli-	m
	10^{-6}	micro-	μ
	10^{-9}	nano-	n

Standard form

Another convenient and acceptable way of expressing physical quantities is to use the **standard form**. Standard form is a way of writing numbers, in which one integer (1 to 9) is multiplied by an appropriate power of 10. For example, 0.005 67 and 16 800 will be expressed in standard form as 5.67×10^{-3} and 1.68×10^4. In the case of 0.01 μm, it can also be expressed as 1×10^{-8} m. Some other common quantities expressed in standard form are shown below:

- One kilometre (km) is 1×10^3 m.
- One milliampere (mA) is 1×10^{-3} A.
- Three megajoules (MJ) is 3×10^6 J.
- Six microcoulombs (μC) is 6×10^{-6} C.
- Eight nanoseconds (ns) is 8×10^{-9} s.

How do we measure length?

In physics, length is an important quantity that is often used. For example, we measure length to find out how far an object has moved, how much space an object occupies (i.e. the object's volume) and how far apart two objects are.

The SI unit for **length** is the **metre (m)**. There is a wide range of lengths in this world from the width of a human hair to the radius of the Earth. It is necessary to use the appropriate instruments and methods to measure different types of length.

ENRICHMENT
THINK

A stack of paper is shown in Figure 1.3. How would you estimate the thickness of a sheet of paper in the stack?

Figure 1.3 *A stack of paper*

The metre rule and measuring tape

The metre rule and measuring tape (Figure 1.2) are instruments that are commonly used to measure length.

A metre rule can measure lengths of up to one metre. A steel measuring tape is suitable for measuring straight distances longer than a metre, while a cloth measuring tape is suitable for measuring the length along a curved surface, such as a person's waist.

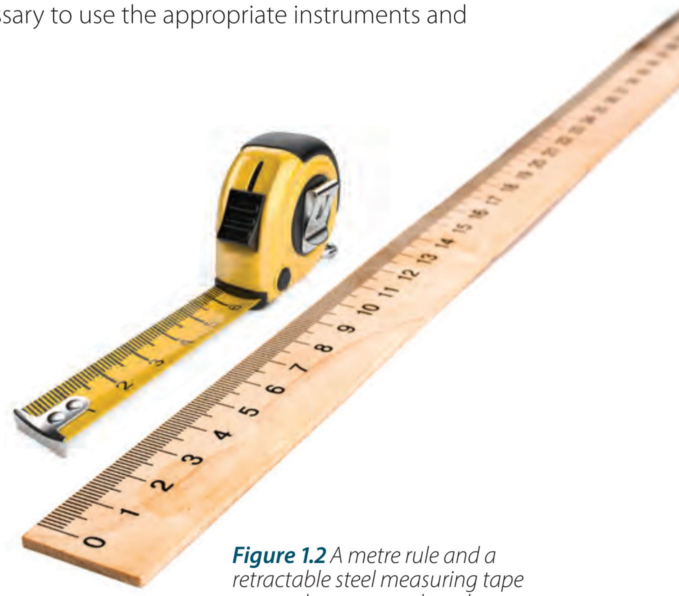


Figure 1.2 *A metre rule and a retractable steel measuring tape are used to measure lengths.*

What is the precision of an instrument?
The smallest unit an instrument can measure is known as its **precision**. What is the smallest unit on a metre rule? It is 0.1 cm or 1 mm. Therefore, the precision of a metre rule is 1 mm.

The thickness of a piece of paper is less than the precision of a metre rule (i.e. 1 mm). Therefore, you cannot measure the paper's thickness directly using a metre rule. You will have to estimate its thickness.

How do we avoid errors in measurement?
When you use a metre rule, your eyes should be positioned such that your line of sight is perpendicular to the rule (Figure 1.4(a)). In other words, you must look at the rule 'straight on', not at an angle. If this is not done, an error will be introduced into the measurement (Figure 1.4(b)). This type of error is called **parallax error**.

QUICK CHECK

When using a metre rule to measure length, I must be careful to avoid parallax error.

True or false?

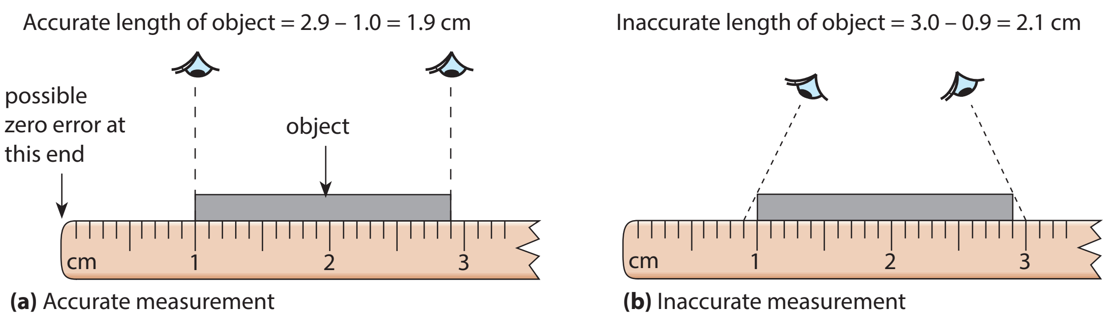


Figure 1.4 *How to take accurate readings by avoiding parallax errors*

A metre rule may have its zero mark at the very end of the rule. It may no longer be suitable for measuring if the zero-mark end is worn. The worn end of the rule may introduce errors into the readings. Hence, it is better to measure from another point and subtract it from the final reading (Figure 1.4(a)). Taking several readings and calculating the **average** also minimises errors.

The vernier calipers

A pair of vernier calipers (Figure 1.5) has a main scale and a sliding vernier scale. It is a useful tool for measuring both the internal and external diameters of small objects. Vernier calipers are able to measure to a precision of 0.01 cm.

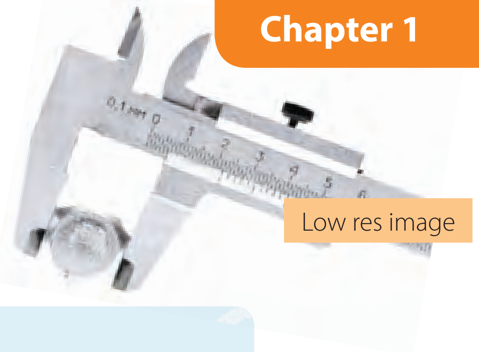
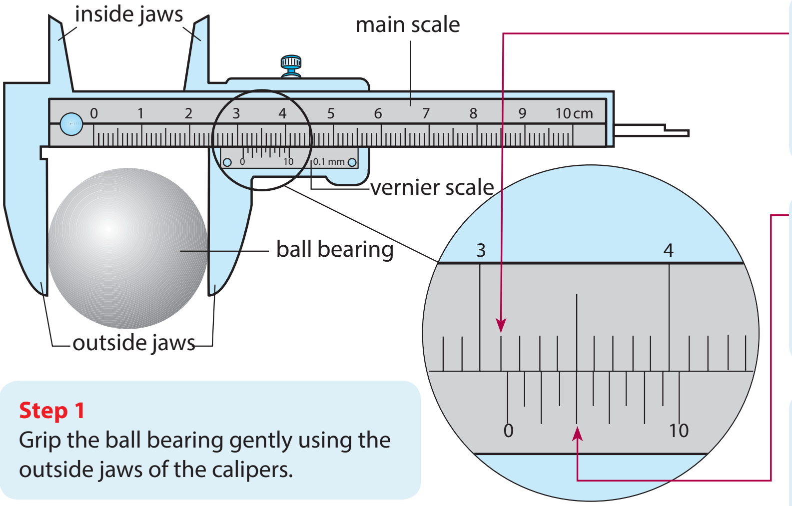


Figure 1.5 *Measuring the diameter of a bolt using vernier calipers*

How do we use the vernier calipers?

Figure 1.6 shows how a pair of vernier calipers is used.



Step 1
Grip the ball bearing gently using the outside jaws of the calipers.

Step 2
Read the main scale to the immediate left of the zero mark on the vernier scale. In this case, the reading on the main scale is 31 mm or 3.1 cm.

Step 3
The 4th vernier mark coincides with a marking on the main scale. This gives a reading of 0.4 mm or 0.04 cm on the vernier scale.

Step 4
The diameter is found by adding the vernier scale reading to the main scale reading:
31 mm + 0.4 mm = 31.4 mm or
3.1 cm + 0.04 cm = 3.14 cm

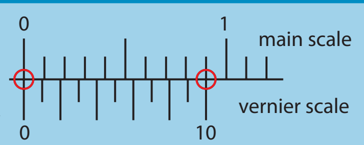
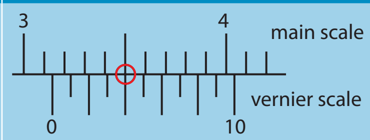
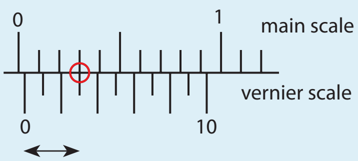
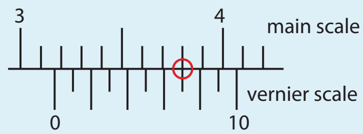
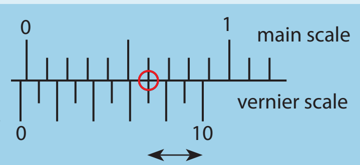
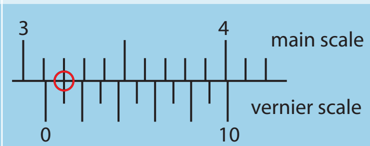
Figure 1.6 *Using the vernier calipers*

How do we avoid errors when using the vernier calipers?

Before using the vernier calipers, we need to examine the instrument for **zero error**.

First, ensure the jaws are touching each other. Then check if the zero mark on the main scale coincides with the zero mark on the sliding vernier scale. Table 1.4 shows how to correct for zero errors on the vernier calipers.

Table 1.4 *Checking and correcting zero errors when using the vernier calipers*

Type of zero error	Example of observed reading	Corrected reading
No zero error The zero marks of the two scales coincide. → 	 Reading = 3.14 cm	3.14 cm (No correction required)
Positive zero error The zero mark of the vernier scale is slightly to the right of the main scale. →  3 divisions Zero error = +0.03 cm	 Reading = 3.17 cm	3.17 – (+0.03) = 3.14 cm
Negative zero error The zero mark of the vernier scale is slightly to the left of the main scale. →  3 divisions Zero error = –0.03 cm	 Reading = 3.11 cm	3.11 – (–0.03) = 3.14 cm

How do we measure volume?

The SI unit for **volume** is the **cubic metre (m^3)**. What are the basic methods of measuring the volumes of solids and liquids?

Volume of regular solids

A metre rule or vernier calipers can be used to measure the dimensions of a regular solid. The volume of the solid can then be determined by using the appropriate formula. Here are some examples:

(a) Volume of a rectangular block = $l \times b \times h$, where l = length, b = breadth and h = height

(b) Volume of a cylinder = $\frac{1}{4}\pi d^2 h$, where d = diameter and h = height

(c) Volume of a sphere = $\frac{4}{3}\pi\left(\frac{d}{2}\right)^3$, where d = diameter

Volume of irregular solids

How do we find the volume of small objects that sink?
By means of a measuring cylinder, we can find the volume of a small object, $V = V_2 - V_1$, where V_1 = volume of water before putting in the object and V_2 = volume reading after putting in the object (Figure 1.7).

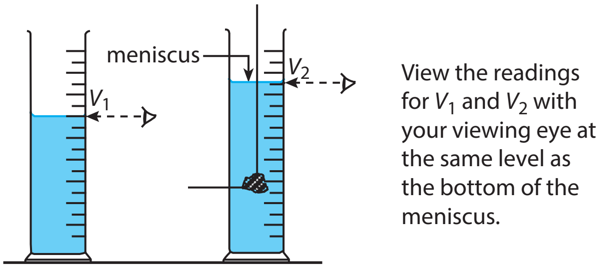


Figure 1.7 Finding the volume of a small object that sinks

How do we find the volume of small objects that float?
For small objects (such as a piece of cork) that float, a sinker such as a lump of metal is used. The sinker ensures that the small object is totally immersed in the water (Figure 1.8).

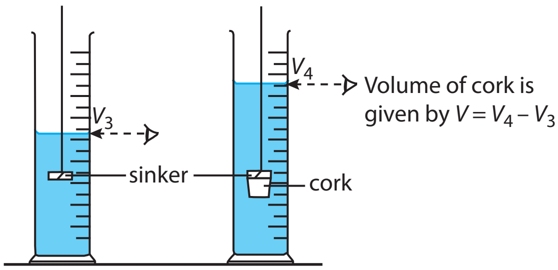


Figure 1.8 Finding the volume of a small object that floats

How do we find the volume of large objects that sink?
For large objects (such as a stone) that sink, we use a displacement can and a measuring cylinder to find the volume (Figure 1.9). Note: In the case of large objects that float, we can use a sinker in the same way as in Figure 1.8.

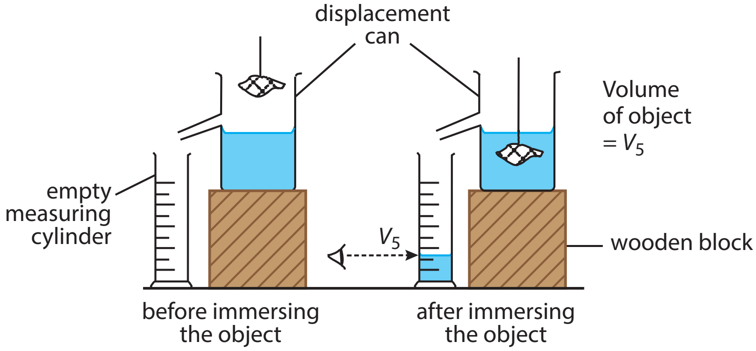


Figure 1.9 Finding the volume of a large object that sinks

Volume of liquids

The volume of a liquid can be found by pouring the liquid into a measuring cylinder and reading the volume V directly (Figure 1.10). Ensure that the measuring cylinder is resting on a flat horizontal surface and that any bubbles in the liquid are removed.

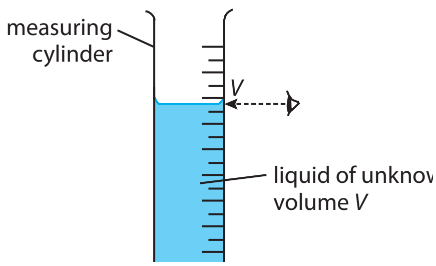


Figure 1.10 Measuring the volume of a liquid

LINK PWB
Practical 1A, pp. XX–XX

How do we measure time?

Imagine that you are stranded on an island. You do not have a watch or a mobile phone. How would you be able to tell the time? We can tell time by observing events that repeat at **regular intervals** or **periods**. Examples of such events are seasons, phases of the Moon, sunsets and positions of the Sun.

The SI unit for **time** is the **second (s)**. The year, month, day, hour and minute are other units for measuring time.

Scientific work cannot rely on the observation of natural events, which are not fixed. For example, the time interval between a sunrise and a sunset is different in winter and summer. The time intervals for scientific work have to be fixed; they cannot change. Can you think of recurrent motions that can be used to measure time for scientific work?

Using a pendulum to measure time

A simple pendulum can be used to measure time. It consists of a heavy object, called a bob (e.g. a metal ball), that is attached to one end of a string. The other end of the string is fixed. When a pendulum swings freely, it will move back and forth at regular intervals.

Each complete to-and-fro motion is one oscillation (Figure 1.11).

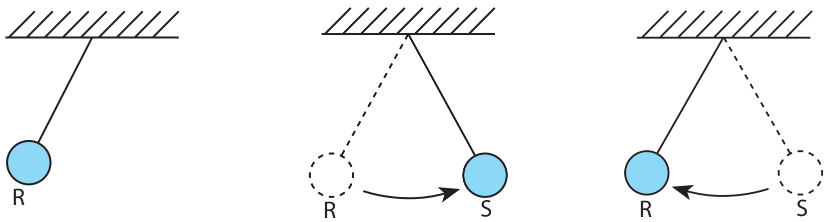


Figure 1.11 When the bob moves from R to S and back to R, the pendulum completes one oscillation. In what other ways can the bob swing to produce one complete oscillation?

The **period** of a simple pendulum is the time taken for one complete oscillation.

The period of a pendulum depends on its length. Pendulum clocks can be calibrated to measure time accurately by adjusting the length of the pendulum.

For scientific work, time intervals have to be precisely measured. The period of the oscillations must not change. Most modern timepieces are calibrated using precise timekeeping devices called atomic clocks (Figure 1.12).

WORD ALERT

Motion: movement

Calibrated: adjusted

Instruments used to measure time

The common instruments used to measure intervals of time in hours, minutes and seconds include clocks and stopwatches.

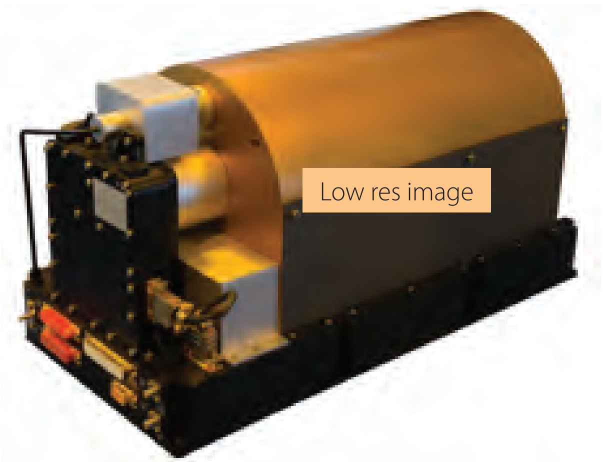


Figure 1.12 This atomic clock used in some satellites can measure time to within 0.45 nanoseconds over 12 hours.

Pendulum clock

All timepieces use some kind of periodic motion to measure time. Pendulum clocks keep time using a pendulum's periodic swing.

Clocks and stopwatches

The oscillations of springs and the natural vibrations of crystals are other periodic motions that can be used to keep time. Most clocks and watches today use quartz crystals. Quartz crystals are small, accurate and require very little electrical energy.

Figure 1.13 shows several instruments that measure time. Depending on the accuracy and precision needed, the instruments used will vary.

Most stopwatches can measure time to a precision of 0.01 s. Digital stopwatches usually show readings up to two decimal places. However, we usually take readings to the nearest one decimal place. This is because we need to start and stop a stopwatch by hand, unlike the electronic sensor used in a data logger. This manual operation introduces a random error called *human reaction time*. Human reaction time is about 0.3–0.5 s for most people.

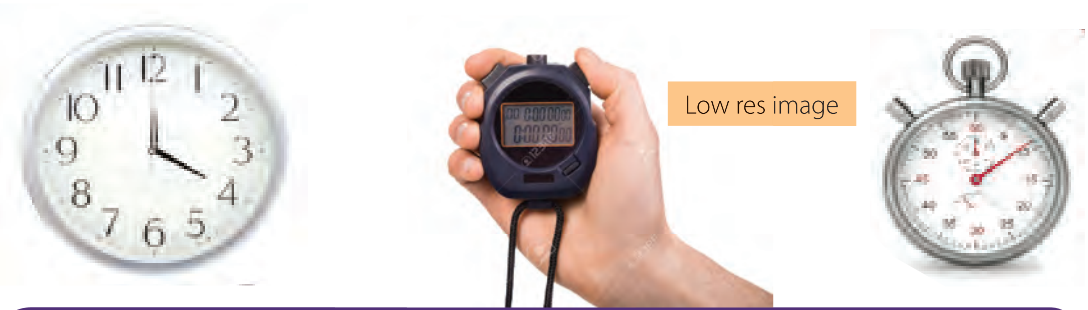


Figure 1.13 *Which time measuring instrument would you use to measure the time taken by a runner to run a 100 m race? Why?*

ENRICHMENT *ACTIVITY*

Use the Internet to find an online reaction time test. Find out what is your average reaction time. Compare your reaction time with those of your classmates.

Let's Investigate 1A

Objective

To calibrate a simple pendulum to measure time in seconds

Apparatus

Pendulum, stopwatch, metre rule, retort stand and clamp

Procedure

1. Tie the pendulum to the clamp and measure the length l of the string in metres (Figure 1.14).
2. Measure the time taken for the pendulum to make 20 oscillations.
3. Vary the length l of the string between 50 and 90 cm and repeat step 2.
4. Complete Table 1.5.

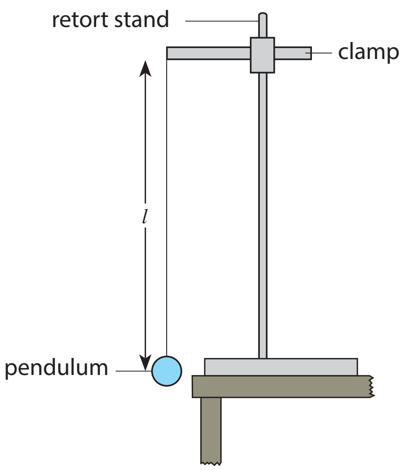


Figure 1.14

Table 1.5

Length l/m	Time for 20 oscillations			Period T/s	T^2/s^2
	t_1/s	t_2/s	t_{ave}/s $\left[t_{ave} = \frac{(t_1 + t_2)}{2}\right]$		
0.500					
0.600					
0.700					
0.800					
0.900					

5 Plot a graph of period T/s against length l/m, and find the length of the pendulum with a period of one second. Plot also a graph of T^2/s^2 against length l/m.

Calculation

The period of the pendulum, T, is found by dividing t_{ave} by 20s, i.e, $T = \frac{t_{ave}}{20}$.

Results and discussion

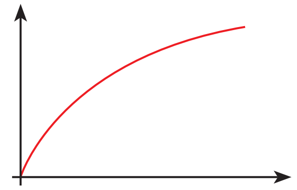


Figure 1.15

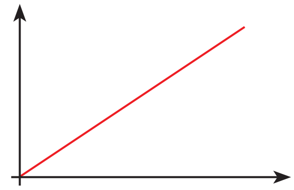


Figure 1.16

How does this experiment allow us to use a pendulum to measure time in seconds?
The length of the pendulum with a period of one second can be read off the graph. By using a pendulum of this length, we can measure time by counting the number of oscillations (e.g. if 1 oscillation takes 1 s, then 60 oscillations take 60 s or 1 min).

What can we observe about the graph of T against l?
The period increases with length but not linearly (Figure 1.15).

What does the plot of T^2 against l tell us?
It tells us that the square of the period is directly proportional to the length. This produces a straight-line graph when we plot T^2 against l (Figure 1.16). By extending the straight-line graph, we can easily predict the period of the pendulum for lengths that are not included in the graph we have plotted.

WORD ALERT

Linearly: in a straight line

LINK

Practical 1B, pp. XX–XX

Worked Example 1A

A student checks the accuracy of an antique clock (Figure 1.17). He uses a digital stopwatch to find the period of the clock's pendulum.

(a) If X and Y are the two extreme positions of each oscillation, state the path of one complete oscillation.

(b) The student's timings for two separate measurements of 20 oscillations are 35.70 s and 34.98 s. Calculate the average period of the clock's pendulum.

Solution

(a) X to Y and back to X **or** Y to X and back to Y.

(b) Average time for 20 oscillations

$= \frac{35.70\text{ s} + 34.98\text{ s}}{2} = 35.34\text{ s}$

Average period of the clock's pendulum $= \frac{35.34\text{ s}}{2} = 1.767\text{ s}$

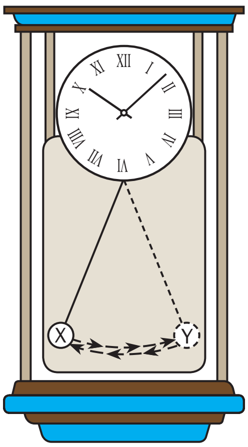


Figure 1.17

QUICK CHECK

In an experiment to find the period of a simple pendulum, we take the time for one complete oscillation.

True or false?

Let's Practise 1.1

1 The world's smallest playable guitar is 10 μm long. Express the guitar's length in standard form.

2 A pair of vernier calipers is used to measure the diameter of a ball bearing. What is the reading of the vernier calipers shown in Figure 1.18?

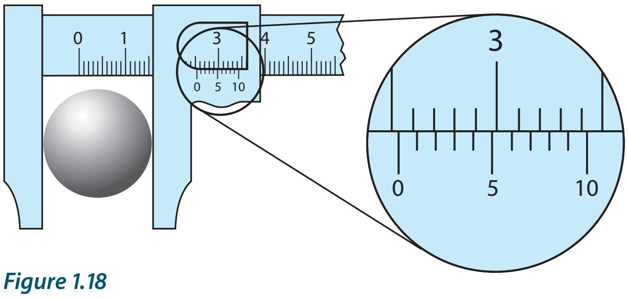


Figure 1.18

3 **(a)** What is the SI unit of volume?

(b) How do we measure the volume of a small irregular object that floats on water?

4 Figure 1.19 shows a voltmeter scale with a strip of mirror mounted under the needle. Suggest how this may help reduce errors when readings are taken.

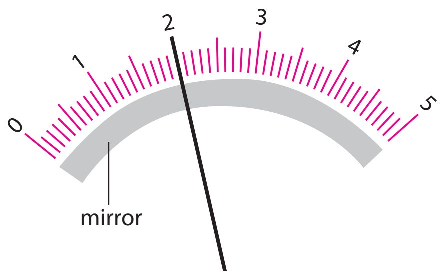


Figure 1.19

5 Figure 1.20 shows an oscillating pendulum. If the time taken for the pendulum to swing from A to C to B is 3 s, what is the period of the pendulum?

6 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

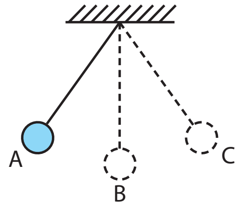


Figure 1.20

LINK TWB

Exercises 1A–1B, pp. X–X

S

1.2 Scalars and Vectors

In this section, you will learn the following:

- S Understand the terms *scalar quantity* and *vector quantity*.
- S Know some examples of scalar and vector quantities.
- S Determine, by calculation or graphically, the resultant of two vectors at right angles.

What are scalars and vectors?

You have learnt that a physical quantity consists of a numerical magnitude and a unit.

A physical quantity can be of two types: scalar or vector.

A **scalar quantity** is a physical quantity that has **magnitude only**.

For example, speed is a scalar quantity because it tells us how fast or slow an object is moving. It does not tell us which direction the object is heading.

To describe speed in a specific direction, we use the term *velocity*. Velocity tells us both how fast or slow an object is moving and in which direction. We say velocity is a vector quantity.

A **vector quantity** is a physical quantity that has both **magnitude and direction**.

Table 1.6 shows some common scalars (scalar quantities) and vectors (vector quantities).

Table 1.6 *Common scalars and vectors*

Scalar	Vector
Speed	Velocity
Distance	Displacement
Time	Force
Mass	Acceleration
Volume	Momentum
Energy	Weight
Temperature	Electric field strength
Electric current	Gravitational field strength

HELPFUL NOTES

Which type of physical quantities have magnitude only and which have both magnitude and direction? To know, remember this line:

Sam **M**agoo has a **V**ery **M**ild **D**iarrhoea.

Can you tell now?

LINK

Why is distance a scalar quantity and displacement a vector quantity?

Find out more in Chapter 2.

Vector diagrams

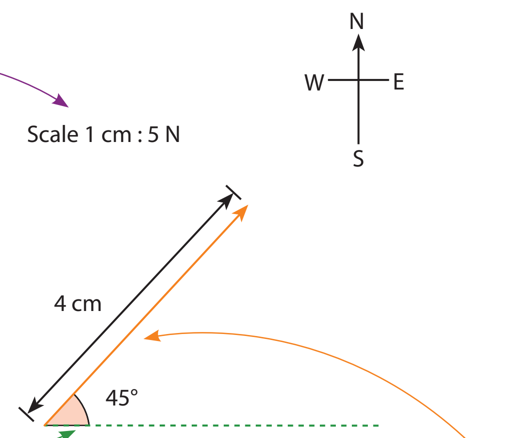
How are vector quantities represented?

Let us take a common example of a vector quantity, namely, force.

A force is a vector — it has both magnitude and direction. Its SI unit is the newton (N). At any time, two or more forces may be acting on an object. The forces may have different magnitudes and directions. In such cases, we can use vector diagrams to add up these forces.

In a vector diagram, a vector quantity is represented by an arrow. The length of the arrow is proportional to the magnitude of the vector. The direction of the arrow indicates the direction of the vector. Figure 1.21 shows the vector diagram of a force of 20 N in the direction 45° north of east.

Step 1
Choose an appropriate scale to represent the force.



Step 2
Draw a base line (horizontal in this case) and measure the required angle with a protractor.

Step 3
Draw an arrow at the angle measured. The length of this arrow should be proportional to the magnitude of the force. This is defined by the scale in Step 1.

Figure 1.21 *Drawing a vector diagram*

How do we add vectors?

Scalars, such as distance and speed, have magnitude and no direction. When we add scalars, we add their magnitudes only.

Unlike scalars, vectors have both magnitude and direction. When we add two or more vectors, we cannot add their magnitudes only. We need to find a single vector that produces the same effect as the vectors combined. The single vector, called the **resultant vector**, must be equivalent to the individual vectors combined in terms of magnitude and direction.

Adding parallel vectors

Let us assign the direction towards the right as positive. Figure 1.22 shows two parallel forces of magnitudes 3 N and 5 N acting on a block. Both forces act in the same direction (i.e. towards the right). The resultant force is 8 N (i.e. 3 N + 5 N = 8 N) and is directed towards the right. A resultant vector is usually indicated by a double-headed arrow.

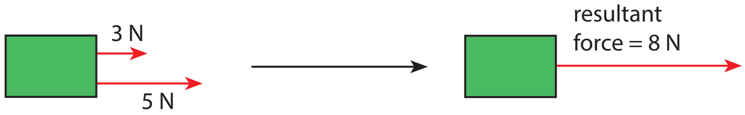


Figure 1.22 Addition of vectors acting in the same direction

In Figure 1.23, the two forces are still parallel but act in opposite directions. The resultant force is 2 N (i.e. 5 N + (–3 N) = 2 N) and is directed towards the right.

Figure 1.23 Addition of vectors acting in opposite directions

In Figure 1.24, two parallel forces of 3 N act on the block in opposite directions.

This produces zero resultant force.

Figure 1.24 Addition of vectors that are equal in magnitude but act in opposite directions

QUICK CHECK

When adding vectors, I must consider both magnitude and direction.

True or false?

Adding non-parallel vectors

Figure 1.25 shows two non-parallel forces, $F_1 = 4$ N and $F_2 = 3$ N, acting on a block at right angle to each other. How can we add the two forces to obtain the resultant force R?

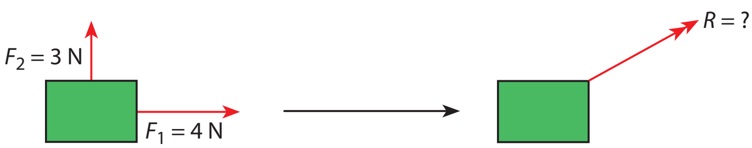


Figure 1.25 Addition of non-parallel vectors

Figure 1.26 shows how we can obtain the resultant force R graphically by drawing a parallelogram. The resultant force R is the diagonal of the parallelogram.

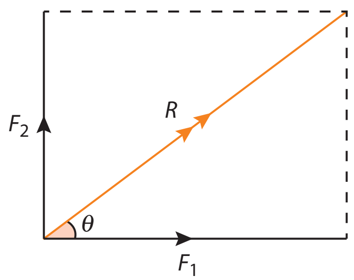


Figure 1.26 *Adding vectors using the parallelogram method (Scale 1 cm: 1 N)*

By measuring the angle θ and the length the diagonal, we obtain the resultant force $R = 5$ N at an angle $\theta \approx 37$°C to the horizontal.

We can also obtain the resultant force R by calculation.

Using Pythagoras' Theorem,

$$R = \sqrt{F_1^2 + F_2^2} = \sqrt{4^2 + 3^2} = \sqrt{25} = 5 \text{ N}$$

$$\tan \theta = \frac{F_2}{F_1} = \frac{3}{4} = 0.75$$

$$\theta = 36.9°$$

Hence, the resultant force R has a magnitude of $R = 5$ N, making an angle of $\theta = 36.9°$ with the horizontal.

By using either the parallelogram method or the calculation method, we arrive at the same answer: the resultant force has a magnitude of 5 N, and acts at an angle of 36.9° to the horizontal.

Let's Practise 1.2

1 Distinguish between a scalar quantity and a vector quantity. Give one example of each.

2 Figure 1.27 shows the forces acting on a box. What is the resultant force?

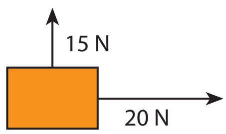


Figure 1.27

3 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

TWB LINK

Exercises 1C–1D, pp. XX–XX

Exercise 1E Let's Reflect, p. XX

Let's Map It

PHYSICAL QUANTITIES

PHYSICAL QUANTITIES — examples with SI units:

- Length (m)
- Volume (m³)
- Time (s)

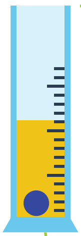
PHYSICAL QUANTITIES — can be classified into:

- S Scalar quantities — have only — S Magnitude
- S Vector quantities — have both —
  - S Magnitude
  - S Direction

Vector quantities (magnitude and direction):

- S Represented by vector diagrams
- S Addition of two vectors to give the resultant vector can be determined graphically or by calculation.

Volume (m³) can be measured using



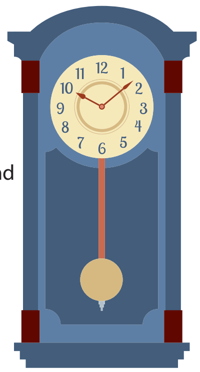
- Measuring cylinder for liquids and small irregular solids
- Formulae for regular solids
- Displacement method for large irregular solids

Time (s) can be measured using

- Clocks and digital timers (e.g. pendulum clocks and stopwatches)

based on

Periodic motions called oscillations



Length (m) can be measured using

Instrument	Precision	Measuring range
Measuring tape	1 mm	Several metres
Metre rule	1 mm	Several cm to1 m
Vernier calipers	0.1 mm	1 cm to 15 cm

Let's Review

Section A: Multiple-choice Questions

1 In a particular experiment, you are required to measure the distance between two points. The two points are between 0.7 m and 0.8 m apart. Which of the following instruments should you use to obtain a reading that has a precision of 0.001 m?

A A half-metre rule
B A metre rule
C A ten-metre measuring tape
D A metre rule and a pair of vernier calipers

2 Figure 1.28 shows two vernier scales. The top vernier scale shows the reading when the vernier calipers are closed. The bottom vernier scale shows the reading when the diameter of a steel ball bearing is being measured.

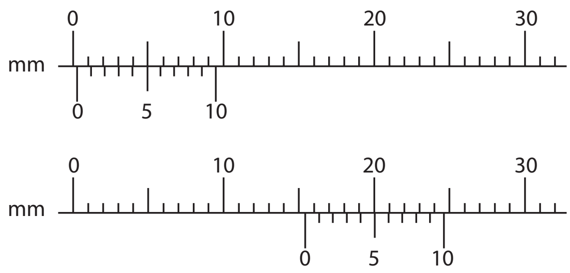


Figure 1.28

What is the diameter of the ball bearing?

A 1.49 cm	**B** 1.50 cm
C 1.59 cm	**D** 1.61 cm

3 When using a measuring cylinder, one precaution to take is to

A check for zero error.
B look at the meniscus from below the level of the water surface.
C obtain more readings by looking from more than one direction.
D position the eye in line with the base of the meniscus.

4 Figure 1.29 shows a simple pendulum.

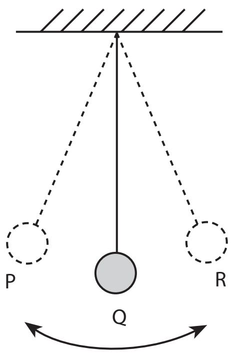


Figure 1.29

Which of the following statements about the period of the pendulum is/are **not** true?

1 It is independent of the mass of the bob.
2 It increases as the length of the pendulum increases.
3 It is the time taken for the bob to swing from Q to P and back to Q.

A 1 and 2 only	**B** 1 and 3 only
C 2 and 3 only	**D** 3 only

5 S Figure 1.30 shows two forces acting at right angle to each other.

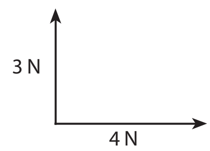
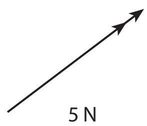


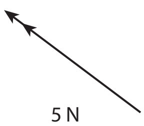
Figure 1.30

Which of the following shows the resultant force?

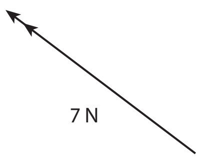
A



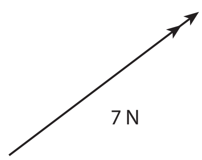
B



C



D



Let's Review

Section B: Short-answer and Structured Questions

1 Identify the physical quantity, numerical magnitude and unit in the following statements:

(a) The length of a table is found to be five metres.

(b) The time the pendulum takes to complete a single oscillation is two seconds.

(c) A typical car has a mass of one thousand kilograms.

2 A student measures the width of a glass slide using a pair of vernier calipers.

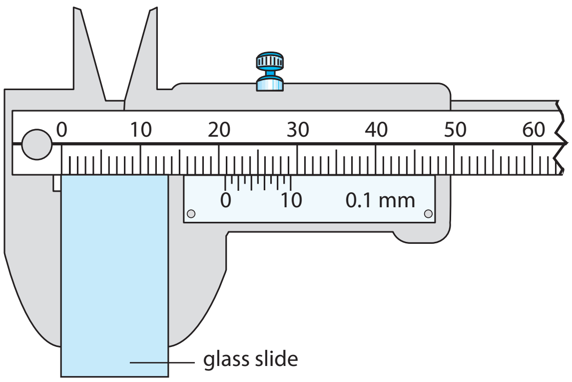


Figure 1.31

(a) In Figure 1.31, what is the measurement of the width of the glass slide?

(b) List the precision of the following measuring instruments: vernier calipers and metre rule.

(c) Explain why the method shown in Figure 1.31 will not yield an accurate measurement.

How would you obtain a more accurate measurement of the width of the glass slide?

3 Describe the method you would use to find the volume of the following:

(a) a matchbox

(b) the cork stopper of a bottle

(c) some liquid perfume in a very small bottle

4 A student conducted an experiment to measure the acceleration due to gravity g of a simple pendulum.

The data obtained were tabulated in Table 1.7.

Table 1.7

Length of thread l/m	0.35	0.65	1.00	1.45	1.95
Time for 20 oscillations t/s	24.1	32.4	40.1	47.5	56.3

The relation between the period T, the length l of the pendulum and the acceleration due to gravity g is

$T = 2\pi\sqrt{\frac{l}{g}}$. Find the value of g using the graphical method.

5 **S** Figure 1.32 shows a lorry that is stuck in muddy ground being pulled by two jeeps. Each jeep exerts a force of 3000 N at an angle of 45° to the horizontal. Using a vector diagram, determine the resultant force on the lorry.

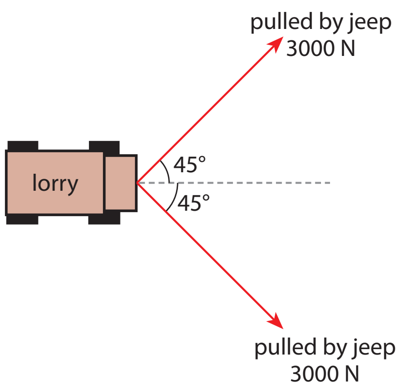


Figure 1.32

CHAPTER

2 Motion

In track and field, the 100-metre race has always been the crowd's favourite. The short-distance race tests an athlete's ability to accelerate to his or her maximum speed.

In the August 2016 Rio Olympics, the winner of the men's 100-metre final, a Jamaican, clocked an amazing time of 9.81 seconds as he crossed the finishing line! With this win, he became the first person in history to win the 100-metre race three times in three consecutive Olympics. His 100-metre timings for the August 2012 London Olympics and the August 2008 Beijing Olympics are 9.63 seconds and 9.69 seconds respectively. His best ever is 9.58 s during the 2009 World Athletics Championship in Berlin.

What an amazing record! If you dream of becoming a fine sprinter, get into MOTION!

PHYSICS WATCH

Scan this page to watch a clip about average speed.

QUESTIONS

- Who is this incredible sprinter from Jamaica?
- Can you spot him in the photo? Is he ahead of the others at this point?
- How did he eventually win the race?

2.1 Speed, Velocity and Acceleration

In this section, you will learn the following:

- Define *speed* and *velocity*.
- Recall and use the equation average speed = $\frac{\text{total distance}}{\text{total time}}$.
- **S** Define *acceleration*.
- **S** Recall and use the equation $a = \frac{\Delta v}{\Delta t}$.

What is speed?

If Usain Bolt were to race against a cheetah in a 100-metre sprint, will the winner be the human king of speed or the animal king of speed (Figure 2.1)?

To find out, we need to compare their speeds. Speed refers to how fast something moves.

Speed is the distance travelled per unit time.

Speed = $\frac{\textbf{distance travelled}}{\textbf{time taken}}$

Its SI unit is **metre per second (m/s)**.

Based on Usain Bolt's 100-metre fastest record time of 9.58 s,

Speed = $\frac{\text{distance travelled}}{\text{time taken}} = \frac{100\ \text{m}}{9.58\ \text{s}} = 10.4\ \text{m/s}$

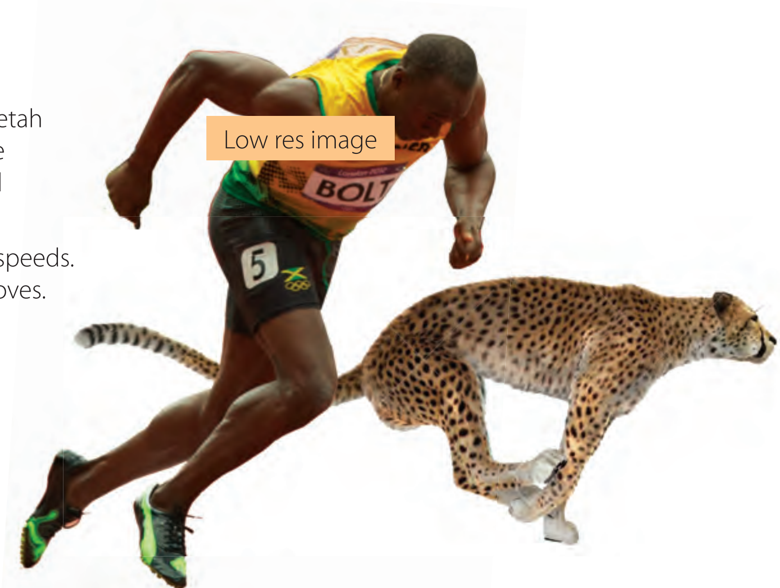


Figure 2.1 *Who is the real king of speed?*

Compare this with the cheetah's average running speed shown in Figure 2.2.

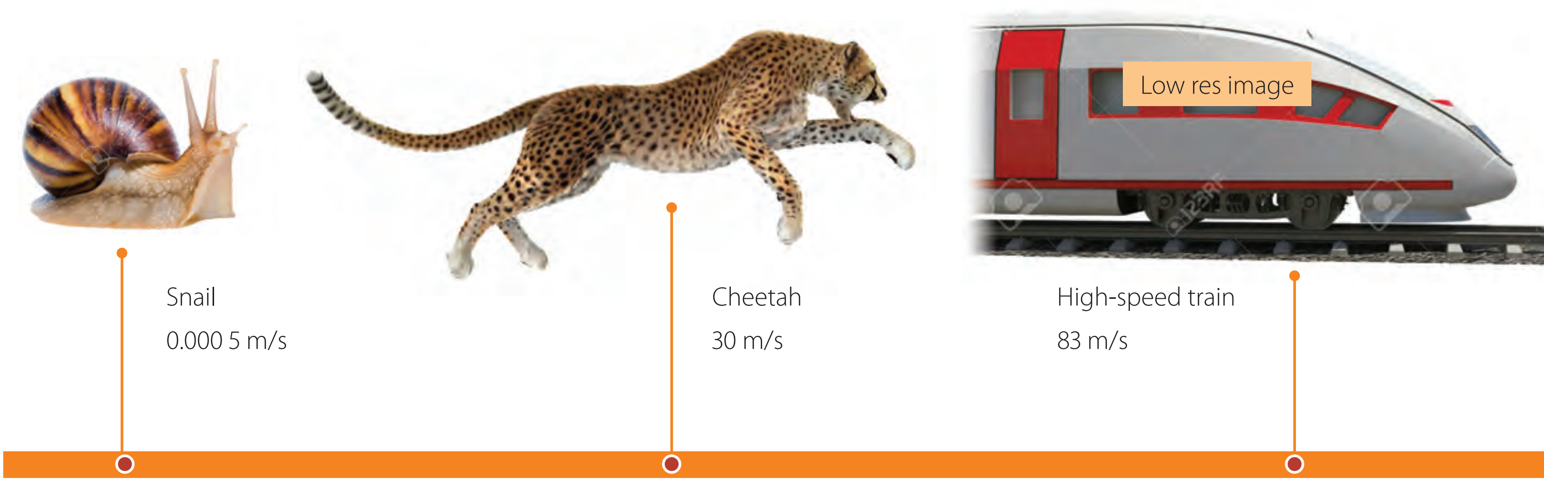


Figure 2.2 *Average speeds of some animals and objects*

What is average speed?

Table 2.1 shows the results for men's running events at the 2016 Rio Olympics.

Table 2.1 *Results for men's running events at the 2016 Rio Olympics*

Athlete	Country	Event/m	Time/s	Speed/m/s
Usain Bolt	Jamaica	100	9.81	10.2
Usain Bolt	Jamaica	200	19.78	10.1
Wayde van Niekerk	South Africa	400	43.03	9.30
David Lekuta Rudisha	Kenya	800	102.15	7.83

The speeds shown in the table are actually average speeds. **Average speed** assumes that each athlete ran at the same speed throughout the entire distance.

$$\textbf{Average speed} = \frac{\textbf{total distance travelled}}{\textbf{total time taken}}$$

In reality, the athletes did not run at the same speed throughout their races. The speed at one instant is different from the speed at another instant. The speed of an object at a particular instant is known as its *instantaneous* speed.

Worked Example 2A

A car travels 6 km in 5 min. Calculate its average speed in m/s.

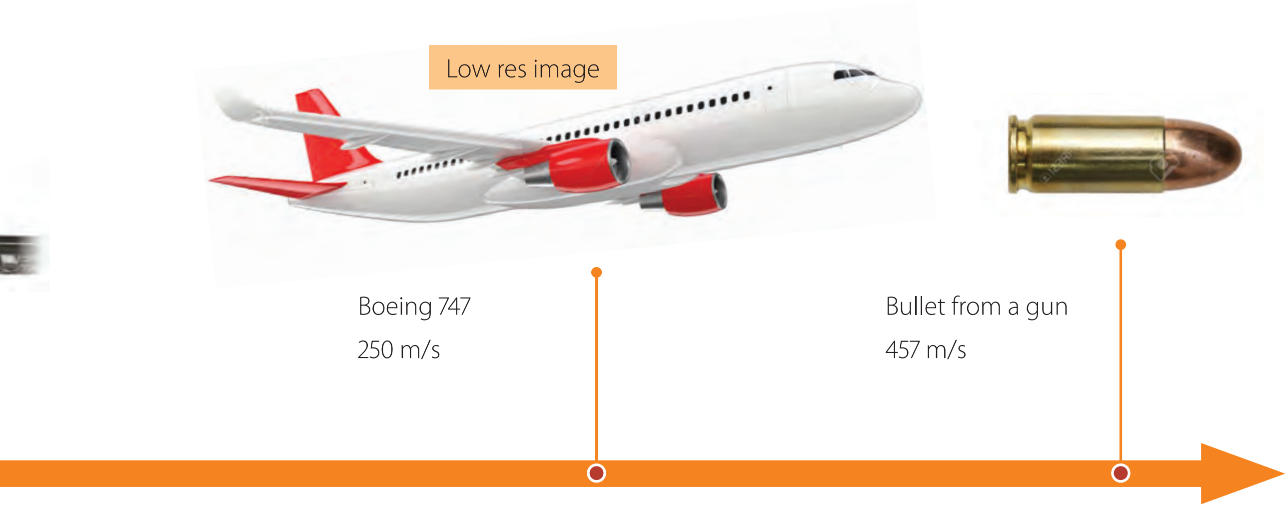
Solution

$$\text{Average speed} = \frac{\text{total distance travelled}}{\text{total time taken}}$$

$$= \frac{6 \times 1000 \text{ m}}{5 \times 60 \text{ s}}$$

$$= 20 \text{ m/s}$$

How does the average speed of a car compare with the other objects and animals shown in Figure 2.2?



WORD ALERT

Instant: a point in time

QUICK CHECK

The actual speed of a car is always the same as its average speed.

True or false?

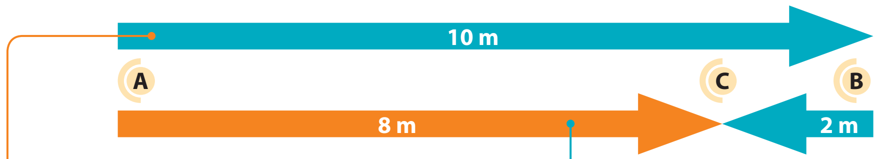
ENRICHMENT INFO

Animal Migration

Animal migration is the seasonal movement of animals from one place to another in search of feeding and breeding grounds. Humpback whales are observed to make some of the longest migrations of any mammals. One of their common migratory routes is between Alaska and Hawaii. The route is about 4830 km one way. The humpback whales can swim from Alaska to Hawaii in 36 days. This works out to an average speed of 5.6 km/h in choppy waters!

How is distance different from displacement?

Figure 2.3 shows the motion of an object from point A to point B and then to point C. We shall use it to illustrate the difference between *distance* and *displacement*.



Distance

- The total length covered by a moving object regardless of the direction of motion
- Has magnitude only
- SI unit: metre (m)
- Distance travelled by the object from A to B, and then to C
  = 10 m + 2 m
  = 12 m

Displacement

- The distance measured in a straight line in a specified direction
- Has both magnitude and direction
- SI unit: metre (m)
- Displacement of the object travelling from A to B, and then to C
  = 10 m − 2 m
  = 8 m (from A to C)
- Refers to the shortest distance and direction of an object from the starting point

Figure 2.3 *Difference between distance and displacement*

Worked Example 2B

Figure 2.4 shows a car that travels 5 km due east and makes a U-turn to travel another 7 km along the same road.

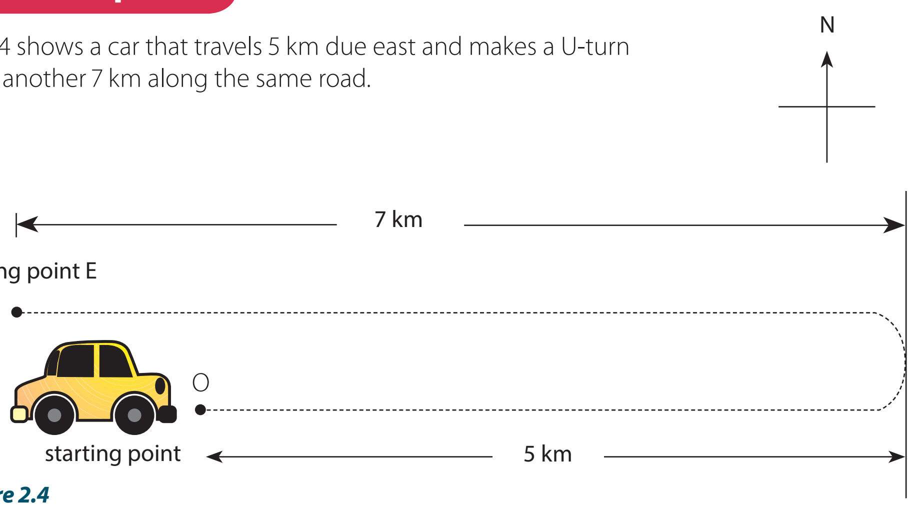


Figure 2.4

Calculate

(a) the distance covered;

(b) its displacement.

Solution

(a) Distance covered = 5 km + 7 km = 12 km

(b) Taking the direction due east of the starting point as positive,

Displacement = 5 km − 7 km = −2 km

It is at a point 2 km due west from the starting point.

LINK

Recall the two types of physical quantities, namely, scalars and vectors, that you have learnt in Chapter 1.

HELPFUL NOTES

For any object moving in a straight line, we can assign a direction from a reference point as positive. As an example, refer to Figure 2.3. If we assign the direction to the right of A as positive, the displacement of the moving object at B is +10 m.

HELPFUL NOTES

The *magnitude* of displacement is the distance measured along a straight line from the starting point to the final point.

Its *direction* is taken from the starting point to the final point.

How is velocity different from speed?

When determining the velocity of an object, we need to know the speed of the object and the direction in which it is travelling. When calculating velocity, we use displacement instead of distance.

Velocity is speed in a given direction. Its SI unit is **metre per second (m/s)**.

$$\textbf{Velocity} = \frac{\textbf{displacement}}{\textbf{time taken}}$$

Similarly, as in the case of average speed,

$$\textbf{Average velocity} = \frac{\textbf{total displacement}}{\textbf{total time taken}}$$

Worked Example 2C

If the runner in Figure 2.5 takes 25 s to run 200 m, calculate her average speed and average velocity.

Solution

$$\text{Average speed} = \frac{\text{total distance travelled}}{\text{total time taken}} = \frac{200\text{ m}}{25\text{ s}}$$
$$= 8\text{ m/s}$$

$$\text{Average velocity} = \frac{\text{total displacement}}{\text{total time taken}} = \frac{50\text{ m}}{25\text{ s}}$$
$= 2$ m/s (from her initial position to her final position)

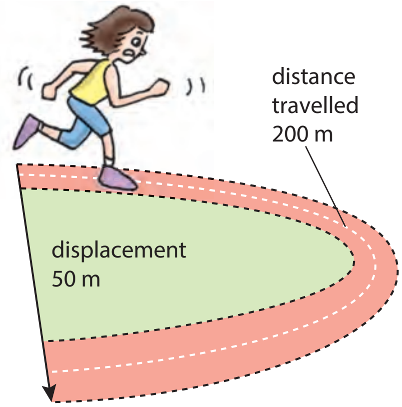


Figure 2.5

QUICK CHECK

Speed is the same as velocity.

True or false?

What is acceleration?

Understanding acceleration

An object is accelerating when its velocity changes. Figure 2.6 shows that an object undergoes acceleration when its speed or direction changes, or when both its speed and direction change.

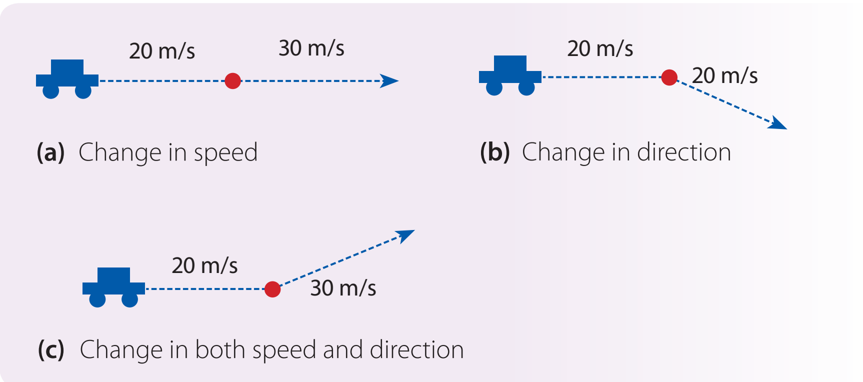


Figure 2.6 *When acceleration occurs*

ENRICHMENT
THINK

In groups of two, discuss whether each of the following events involves acceleration:

1. A space shuttle blasting off
2. An airplane landing
3. A lift approaching a given floor
4. A train leaving a station
5. A car coming to a stop

QUICK CHECK

An object is accelerating when its speed changes. True or false?

When the change (increase or decrease) in the velocity of an object for every unit of time is the same, the object undergoes **constant** or **uniform** acceleration (Table 2.2).

Table 2.2 *Object moving with uniform acceleration*

Time/s	Velocity/m/s			
1	20	+20	80	−20
2	40	+20	60	−20
3	60	+20	40	−20
4	80	+20	20	−20
5	100		0	

From Table 2.2, when the velocity of the object is increasing by 20 m/s every second, the acceleration is 20 m/s². When the velocity of the object is decreasing by 20 m/s every second, the object is said to be undergoing a **deceleration** of 20 m/s.

ENRICHMENT ACTIVITY

Find out whether a stone undergoes acceleration when it is whirled in circles.

1 Tie a string to a small stone.
2 Whirl the stone in circles as shown in Figure 2.8.
3 In small groups, discuss whether the stone undergoes acceleration. Explain your answer.

Figure 2.8 *Whirling a stone*

S Calculating acceleration

Acceleration is the change of velocity per unit time. Its SI unit is **metre per second per second (m/s²)**.

$$\textbf{Acceleration } a = \frac{\textbf{change of velocity}}{\textbf{time}} = \frac{(v - u)}{t} = \frac{\Delta v}{\Delta t}$$

where v = final velocity, u = initial velocity and t = total time taken

Worked Example 2D

A car at rest starts to travel in a straight path. It reaches a velocity of 12 m/s in 4 s (Figure 2.7). Calculate its acceleration.

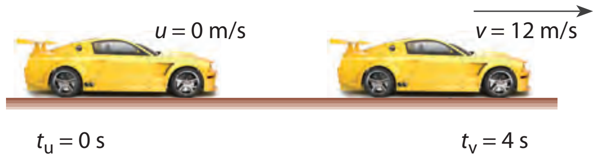


Figure 2.7

Solution

We assign the direction to the right as positive.

Given: Initial velocity $v_1 = 0$ m/s (since the car starts from rest)

Final velocity $v_2 = 12$ m/s

Time taken = 4 s

$$a = \frac{\Delta v}{\Delta t} = \frac{v - u}{t_v - t_u} = \frac{(12 - 0)\text{ m/s}}{(4 - 0)\text{ s}} = 3\text{ m/s}^2$$

The acceleration is 3 m/s² in its travelling direction.

Let's Practise 2.1

1 A toy car travels 96 m in 12 s. Calculate its average speed.
2 S The velocity of a golf ball rolling in a straight line changes from 8 m/s to 14 m/s in 10 s. Calculate its acceleration.
3 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

Exercises 2B, pp. XX-XX

2.2 Graphs of Motion

In this section, you will learn the following:

- Sketch, plot and interpret distance–time and speed–time graphs.
- Determine qualitatively, from given data or the shape of a distance–time graph or speed–time graph, when an object is at rest, moving with constant speed, accelerating or decelerating.
- Calculate speed from a distance–time graph.
- Calculate the area under a speed–time graph to determine distance travelled.
- S Determine when an object is moving with constant or changing acceleration from given data or the shape of a speed–time graph.
- S Calculate acceleration from a speed–time graph.
- S Know what is meant by deceleration and use this in calculations.

Distance–time graphs

By studying the distance–time graph of an object (Figure 2.9), we can get some information about the motion of the object. In what way will the distance–time graph change if the object travels a longer distance at a uniform speed?

The motion of the object is described in Table 2.3.

Table 2.3 *Motion of an object*

Section	Motion of an object
A to B	The graph is a horizontal line. The distance travelled does not change with time. The object is not moving.
B to C	The graph has a constant positive gradient. The distance travelled increases uniformly. The object is moving at a uniform speed.
C to D	The graph is a horizontal line. The distance travelled does not change with time. The object is not moving.
D to E	The graph has a constant positive gradient. The distance travelled increases uniformly. The object is moving at a uniform speed. The graph is less steep here compared to section B to C. Therefore, the object has a lower speed here.

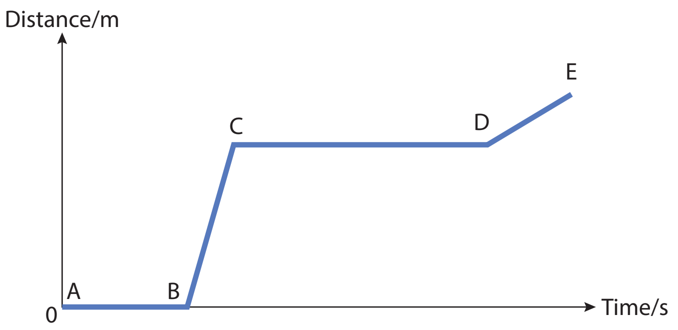


Figure 2.9 *Distance–time graph of a moving object*

ENRICHMENT ACTIVITY

Sketch a distance–time graph for your journey from your home to your school. Then, exchange graphs with a classmate and discuss the differences between your graphs.

Gradient of distance–time graphs

The gradient of a distance–time graph of an object gives the speed of the object.

Figure 2.10 shows a car travelling away from the starting point O. The car travels in one direction only.

Figure 2.10 *Motion of a car*

PHYSICS WATCH

Scan this page to explore distance–time graph simulation.

The distance–time graphs below show four possible journeys of the car.

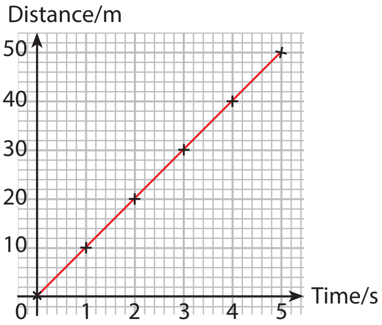


Figure 2.11 *Car travelling at a uniform speed*

Time/s	0	1	2	3	4	5
Distance/m	0	10	20	30	40	50

- The graph has a constant gradient.
- The distance increases 10 m for every second.
- Gradient $= \dfrac{50-0}{5-0} = 10$

  $\therefore$ Speed = 10 m/s

QUICK CHECK

For an object that is not moving, its distance–time graph is a horizontal line.

True or false?

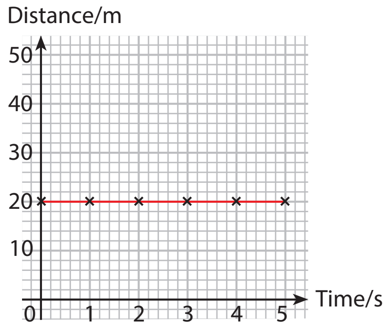


Figure 2.12 *Car stopped or car at rest*

Time/s	0	1	2	3	4	5
Distance/m	20	20	20	20	20	20

- The graph has zero gradient.
- The distance remains at 20 m.
- Speed = 0 m/s

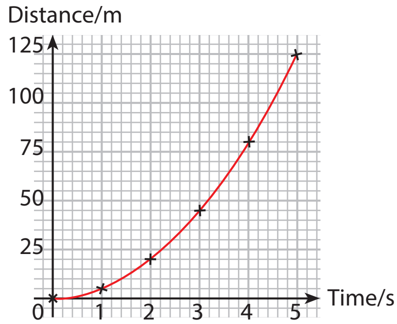


Figure 2.13 *Car travelling with an increasing speed*

Time/s	0	1	2	3	4	5
Distance/m	0	5	20	45	80	125

- The graph has an increasing gradient.
- The speed of the car increases. It travels faster each second.

QUICK CHECK

The constant gradient of a slope in a distance–time graph indicates that an object is moving at a uniform speed.

True or false?

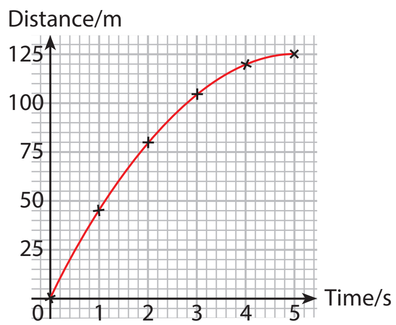


Figure 2.14 *Car travelling with a decreasing speed*

Time/s	0	1	2	3	4	5
Distance/m	0	45	80	105	120	125

- The graph has a decreasing gradient.
- The speed of the car decreases. It travels slower each second.

Speed–time graphs

Area under speed–time graphs

Figure 2.15 shows the speed–time graph for an object moving from one place to another over a time interval of 24 seconds. Based on the graph, how can we describe the motion of the object? What is the distance travelled by the object?

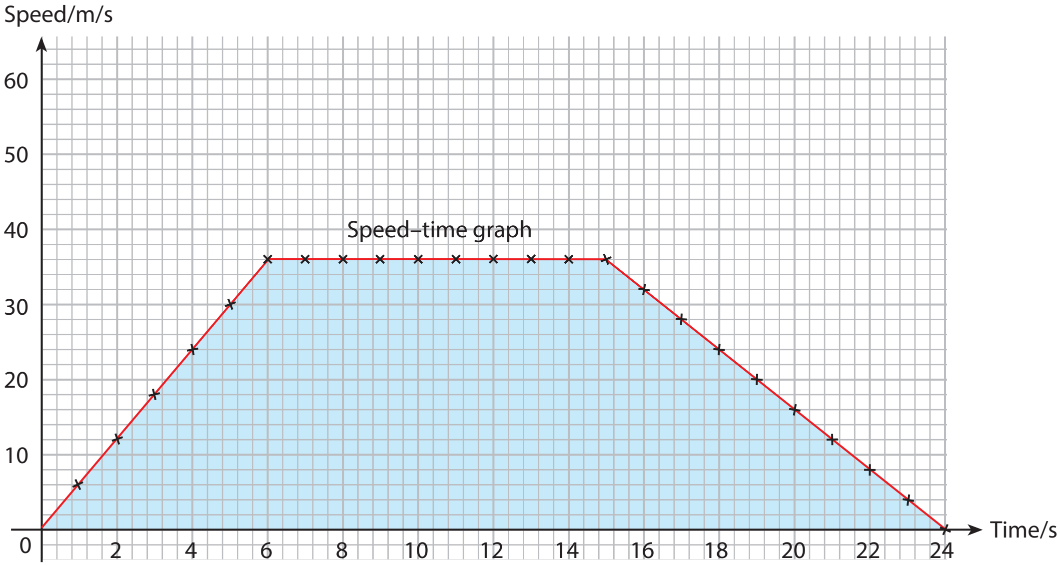


Figure 2.15 *Speed–time graph of an object moving from one place to another*

At $t = 0$ s, the object is at rest. From $t = 0$ s to 6 s, the speed of the object increases uniformly from 0 m/s to 36 m/s, and remains constant at 36 m/s from 6 s to 15 s. From 15 s to 24 s, the speed of the object decreases from 36 m/s to 0 m/s.

For an object travelling with uniform acceleration, the area under its speed–time graph gives the distance it travels.

From Figure 2.15, the total area under the speed–time graph

= area of the trapezium

$= \frac{1}{2} \times \text{sum of parallel sides} \times \text{height} = \frac{1}{2} \times (9 + 24) \times 36 = 594$

Therefore, the total distance travelled by the object is 594 m.

WORD ALERT

Trapezium: a four-sided shape with two parallel sides

Worked Example 2E

Figure 2.16 shows the speed–time graph for an object moving with a uniform speed.

What is the total distance travelled from $t = 0$ s to $t = 10$ s?

Solution

Area under speed–time graph

= area of the rectangle

$= 10 \times 6$

$= 60$

Total distance travelled from $t = 0$ s to $t = 10$ s is 60 m.

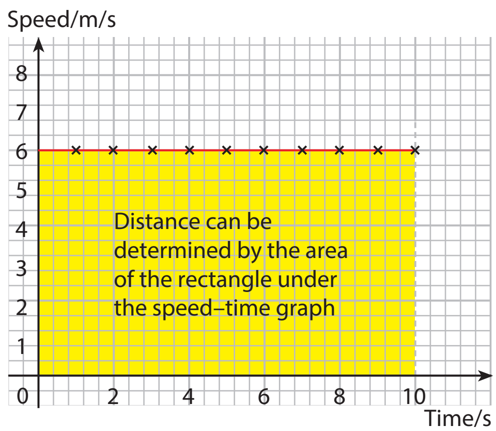


Figure 2.16

HELPFUL NOTES

In Figure 2.15, the object accelerates from rest to 36 m/s in 6 s. It then remains at this speed for 9 s (acceleration = 0 m/s^2). Finally, it decelerates to 0 m/s in 9 s.

In Figure 2.16, the object travels at 6 m/s (acceleration = 0 m/s^2) throughout the journey.

Gradient of speed–time graphs

The gradient of a speed–time graph gives the acceleration of the object.

Based on Figure 2.15 on page 25, the acceleration of the object can be calculated as shown in Table 2.4.

Table 2.4 *Calculating the acceleration of the object*

Time interval	Initial speed *u* and final speed *v*	Acceleration
0 s to 6 s	$u = 0$ m/s, $v = 36$ m/s	$\frac{(36 - 0)\text{ m/s}}{(6 - 0)\text{ s}} = 6\text{ m/s}^2$
6 s to 15 s	$u = 36$ m/s, $v = 36$ m/s	$\frac{(0 - 0)\text{ m/s}}{(15 - 6)\text{ s}} = 0\text{ m/s}^2$
15 s to 24 s	$u = 36$ m/s, $v = 0$ m/s	$\frac{(0 - 36)\text{ m/s}}{(24 - 15)\text{ s}} = -4\text{ m/s}^2$

Uniform and non-uniform acceleration

A train leaves a station and travels along a straight track towards the next station.

Figure 2.17 shows how the speed of the train varies with time over the whole journey.

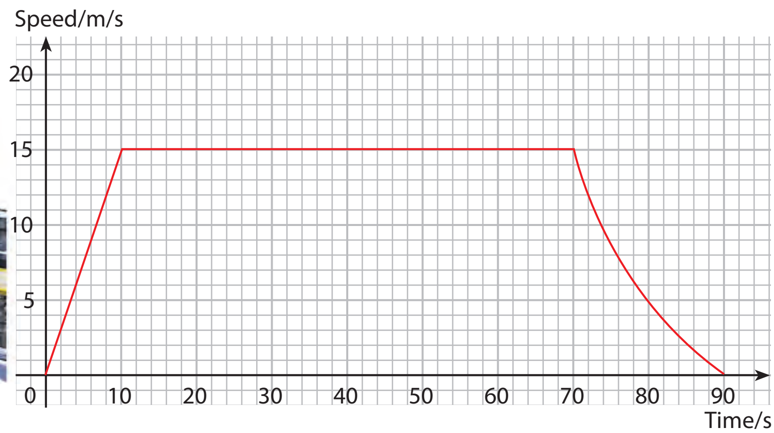


Figure 2.17 *Speed–time graph of a train*

QUICK CHECK

The non-uniform acceleration of an object is shown by the changing gradient of the speed–time graph.

True or false?

Table 2.5 describes how the motion of the train changes over the whole journey (Figure 2.17).

Table 2.5 *Motion of the train*

Time interval	Speed of train	Acceleration of train
0 s to 10 s	• The speed is increasing uniformly. • The gradient remains constant.	The acceleration of the train is uniform.
10 s to 70 s	• The speed remains constant at 15 m/s. • The gradient is zero.	The acceleration of the train is zero.
70 s to 90 s	• The speed is decreasing non-uniformly. • The gradient is becoming less negative (the slope becomes less steep).	• The acceleration of the train is **negative** (deceleration) and non-uniform. • The deceleration of the train is decreasing.

Worked Example 2F

A motorist approaches a traffic light junction at 15 m/s. The traffic light turns red when he is 30 m from the junction. He takes 0.4 s before applying the brakes and his car slows down at a rate of 3.75 m/s² for a time interval of Δt before coming to a stop at time T.

Figure 2.18 shows the speed–time graph of this motorist.

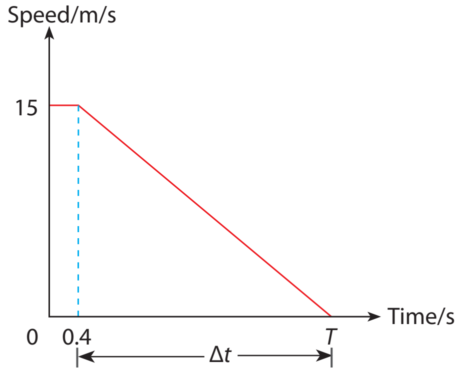


Figure 2.18

(a) Describe in words the speed and acceleration of the car between

(i) $t = 0$ s and $t = 0.4$ s;

(ii) $t = 0.4$ s and $t = T$ s.

(b) What do you call this duration of 0.4 s?

(c) Calculate the value of Δt.

(d) What is the total distance travelled by the car from $t = 0$ s to $t = T$ s?

(e) Is the motorist able to stop his car in time?

WORD ALERT

Duration: length of time, period

Solution

(a) (i) The car travels at a uniform speed of 15 m/s with zero acceleration.

(ii) The speed of the car decreases from 15 m/s to zero with a uniform deceleration of 3.75 m/s².

(b) Human reaction time

(c) Given: Uniform deceleration = 3.75 m/s² (i.e. acceleration $a = -3.75$ m/s²)

Change in velocity Δv = final velocity − initial velocity = (0 −15) = −15 m/s

(d) By definition, $a = \dfrac{\Delta v}{\Delta t} = -3.75 \text{ m/s}^2 = \dfrac{-15 \text{ m/s}}{\Delta t}$

$\therefore \Delta t = 4$ s

(e) Distance = area under speed–time graph

$= \text{area of trapezium} = \dfrac{1}{2} \times (0.4 \text{ s} + 4.4 \text{ s}) \times 15 \text{ m/s}$

$= 36$ m

Since the distance of his car is more than 30 m, the motorist is unable to stop his car in time.

HELPFUL NOTES

The symbol Δ means *change*. So Δt means *change in t*, i.e., final t minus initial t.

Let's Practise 2.2

1 Figure 2.19 shows the distance–time graph of an object from its starting point.

Describe the motion of the object in terms of both its distance from the starting point and its speed at

(a) $t = 0$ s;

(b) $t = 20$ s;

(c) $t = 40$ s.

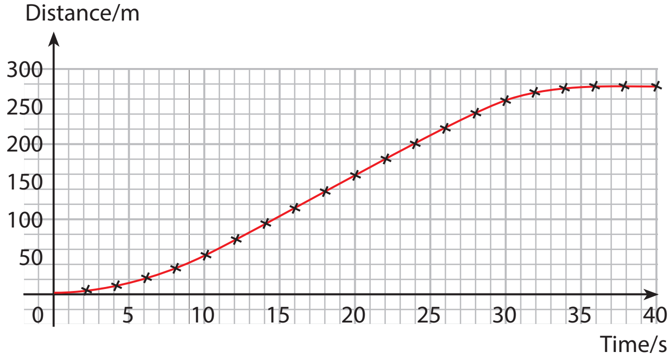


Figure 2.19

2 S The speed–time graph of a car is shown in Figure 2.20.
Describe the motion of the car in terms of both its speed and acceleration for the following time intervals:

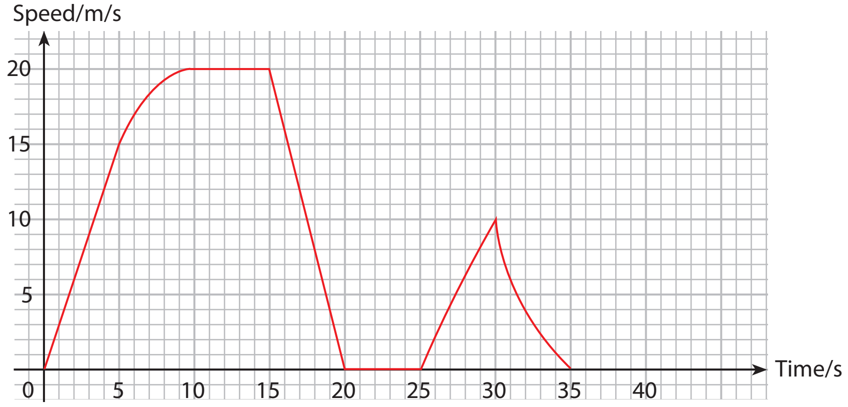


Figure 2.20

(a) $t = 0$ s to $t = 5$ s
(b) $t = 5$ s to $t = 10$ s
(c) $t = 10$ s to $t = 15$ s
(d) $t = 15$ s to $t = 20$ s
(e) $t = 20$ s to $t = 25$ s
(f) $t = 25$ s to $t = 30$ s
(g) $t = 30$ s to $t = 35$ s

3 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK PWB
Practical 2, pp. XX–XX

LINK TWB
Exercises 2B–2C, pp. XX-XX

2.3 Acceleration of Free Fall

In this section, you will learn the following:

- State that the acceleration of free fall g for an object near to the surface of the Earth is approximately constant and is approximately 9.8 m/s^2.
- S Describe the motion of objects falling in a uniform gravitational field with and without air resistance.

What did Galileo discover?

If we drop a large stone and a small pebble from the same height at the same time, which object will hit the ground first?

In the 17th century, Galileo Galilei discovered that all objects fell at the same acceleration due to the Earth's gravity, regardless of mass or size. To make his discovery, Galileo did a series of experiments and careful observations. Galileo's finding was different from Aristotle's widely accepted claim (Figure 2.21).

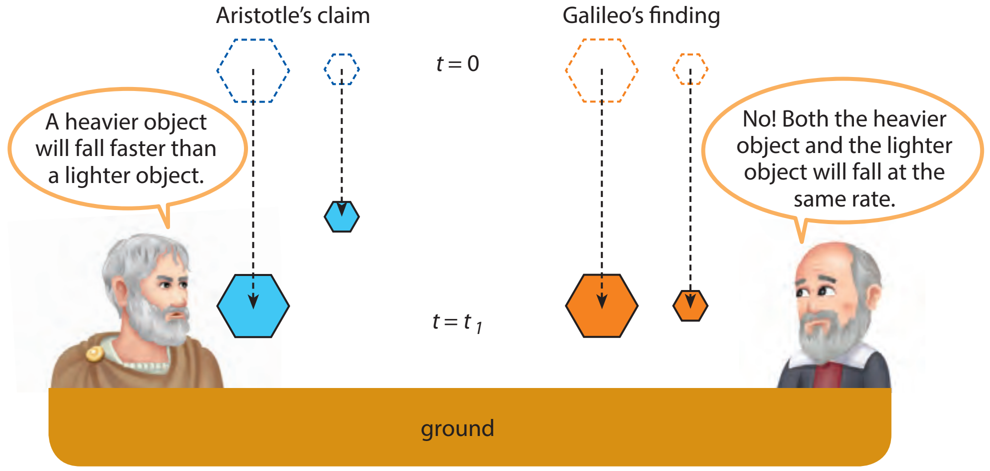


Figure 2.21 *If you were a scientist in the 17th century, would you have accepted Galileo's finding? Why?*

Acceleration due to gravity, ***g***, is a constant for objects close to the Earth's surface. The value of g is generally taken to be 9.8 m/s^2. For simplicity in calculations, we will approximate this value to 10 m/s^2 throughout this book, unless otherwise stated.

PHYSICS WATCH

Scan this page to watch a clip of the feather and hammer experiment.

How do objects fall without air resistance?

An object can only be in **free fall** if the only force acting on it is its own weight. Figure 2.22 shows the paths taken by a feather and by a hammer falling in a vacuum.

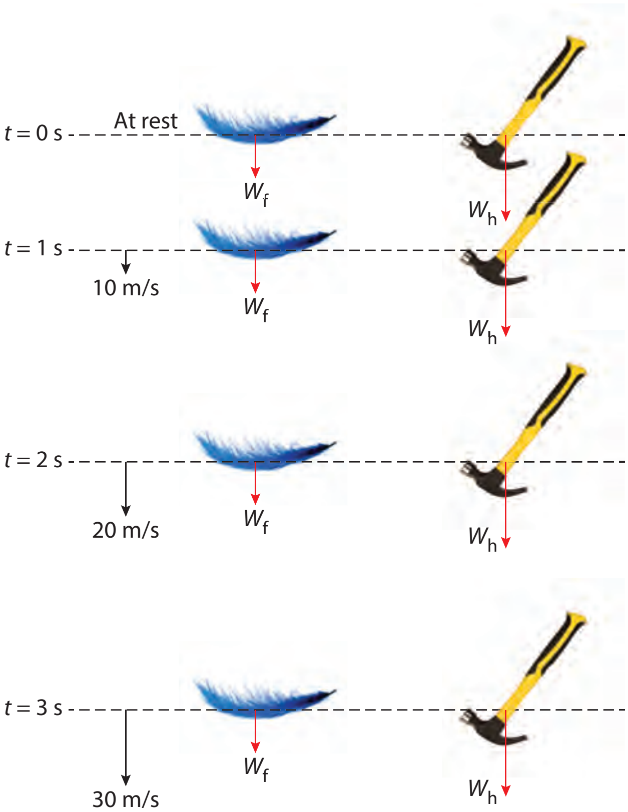


Figure 2.22 A feather and a hammer in free fall

From Figure 2.23, we can make the following deductions:

- The direction of motion for the two objects is downward.
- They fall towards the centre of the Earth.
- Their speed under gravity increases by 10 m/s every second.
- That means both objects have a uniform acceleration of 10 m/s^2.
- The acceleration of free-falling objects does not depend on their mass or size.
- All objects fall freely at a uniform acceleration of 10 m/s^2 near the Earth's surface. Figure 2.23 describes the motion of free-falling objects.

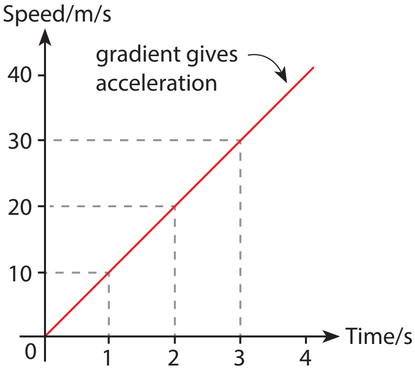


Figure 2.23 Speed–time graph of free-falling motion

WORD ALERT A-Z

Negligible: so small that it can be ignored

Worked Example 2G

Object A was dropped from the third floor. The time taken for the object to reach the ground was 1.34 s. Assume that air resistance was **negligible**. Figure 2.24 shows the path of the free-falling object.

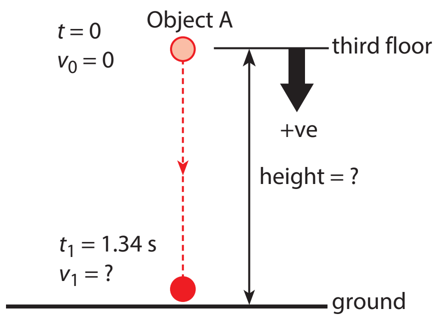


Figure 2.24

(a) Calculate the speed of object A just before it hit the ground.

(b) Calculate the height of the third floor from the ground.

(c) Object B, which was lighter than object A, was dropped from the same third floor. State and explain whether there would be any change in the speed–time graph of object B compared to that of object A.

Solution

Since air resistance was negligible, the object was in free fall (i.e. accelerating at 10 m/s^2).
Given: Time taken t to reach the ground is $t_1 = 1.34$ s

To visualise the problem, we sketch the path and the speed–time graph for free-falling object A (Figure 2.25).

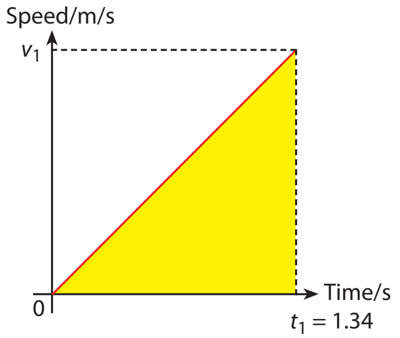


Figure 2.25

(a) Gradient of speed–time graph $= \dfrac{v_1 - 0}{1.34 - 0}$

Uniform acceleration due to gravity = 10 m/s^2

$$\therefore \frac{v_1 - 0}{1.34 - 0} = 10$$

$$v_1 = 13.4 \text{ m/s}$$

The speed of object A just before it hit the ground was 13.4 m/s.

(b) Area under speed–time graph $= \dfrac{1}{2} v_1 t_1 = \dfrac{1}{2} \times 13.4 \text{ m/s} \times 1.34 \text{ s} = 9 \text{ m}$

The height of the third floor from the ground was 9 m.

(c) No. Both object A and object B would have the same speed–time graph, since they fell at a constant acceleration of 10 m/s^2.

How do objects fall with air resistance?

When you run fast, do you feel air brushing against you?
If you do, you are experiencing air resistance.
A parachutist makes use of air resistance to land safely on the ground (Figure 2.26).

Air resistance is a form of frictional force. It has the following characteristics:

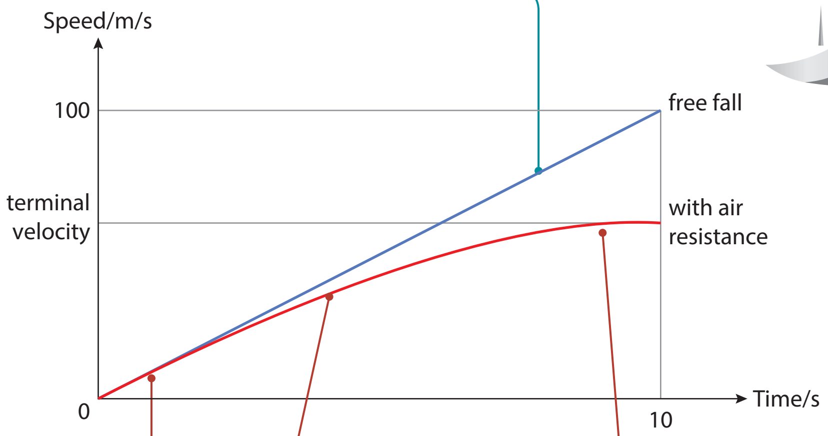
- It opposes the motion of moving objects.
- It increases with the surface area (or size) of moving objects.
- It increases with the density of air.
- It increases with the speed of moving objects.

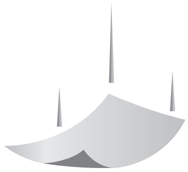
Figure 2.27 describes the motion of a small piece of paper in free fall and the motion of the same paper experiencing air resistance.

Figure 2.26 *Air resistance at work*

Paper in free fall

- The only force acting on an object in free fall is its own weight.
- The paper accelerates uniformly at 10 m/s^2 as it falls. It reaches a speed of 100 m/s in 10 s.





Paper experiencing air resistance

- An object experiences greater air resistance when its speed increases.
- The paper accelerates at 10 m/s^2 initially.

- The acceleration starts to decrease due to the increasing air resistance.

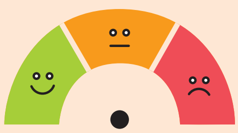
- When the weight of the paper balances the air resistance, its acceleration decreases to zero.
- The paper continues to fall at a uniform velocity known as **terminal velocity**.

Figure 2.27 *Motion of falling paper with and without air resistance*

QUICK CHECK

A feather falls at the same acceleration as a stone in the absence of air resistance.

True or false?



Worked Example 2H

A window cleaner drops a sponge from a window at time $t = 0$ s. Figure 2.28 shows the speed–time graph of the sponge falling.

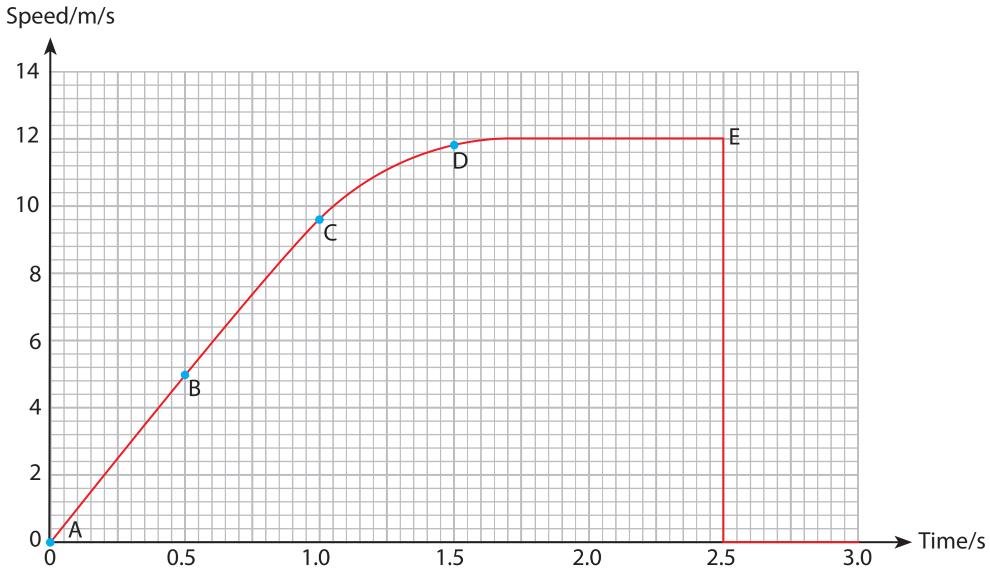


Figure 2.28

(a) Describe the motion of the sponge between A and E.

(b) Calculate the distance that the sponge falls through between $t = 0$ s and $t = 0.6$ s.

Solution

(a) From A to B, the speed of the sponge increases uniformly at a rate of 10 m/s^2.
From B to D, its speed is still increasing but at a decreasing rate.
The acceleration decreases.
From D to E, the sponge has zero acceleration and reaches its terminal velocity of 12 m/s.

(b) Distance = Area under speed–time graph $= \frac{1}{2} \times 0.6 \text{ s} \times 6.0 \text{ m/s} = 1.8 \text{ m}$

Let's Practise 2.3

1 An object is released from an unknown height and falls freely for 5 s before it hits the ground.

(a) Sketch the speed–time graph for a time interval of 5 s, assuming there is negligible air resistance.

(b) Calculate the speed of the object just before it hits the ground.

(c) Calculate the unknown height.

2 S Why does a feather reach terminal velocity faster than a hammer, even though both are released from the same height?

3 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

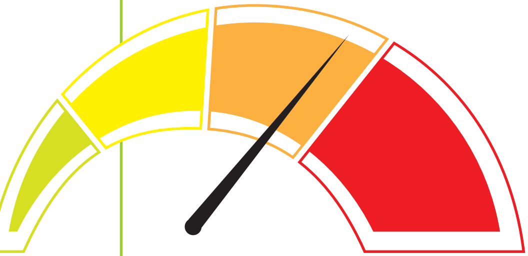
Exercises 2D–2E, pp. XX-XX

Exercise 2F Let's Reflect, p. X

Let's Map It

MOTION

is described in terms of



Speed (m/s)
- scalar

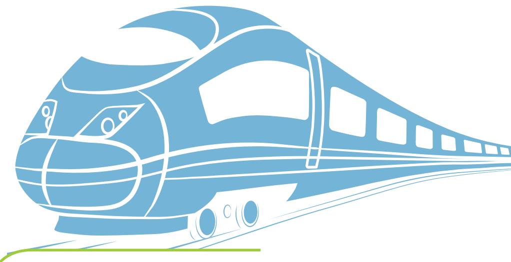
involves
- Distance (m)

can be found by
- Area under speed–time graph

can be found by
- Speed = $\dfrac{\text{distance travelled}}{\text{time taken}}$
- Average speed = $\dfrac{\text{total distance travelled}}{\text{total time taken}}$
- Gradient of distance–time graph

Velocity (m/s)
- vector

involves
- Displacement (m)



can be found by
- Velocity = $\dfrac{\text{displacement}}{\text{time taken}}$

Acceleration (m/s²)
- vector

can be found by
- S Acceleration = $\dfrac{\text{change in velocity}}{\text{time}}$
- S Gradient of speed–time graph

example
- Acceleration of free fall, $g = 9.8\ \text{m/s}^2$
  - S without air resistance, object falls with constant acceleration
  - S with air resistance, object falls with decreasing acceleration and may reach terminal velocity

Let's Review

Section A: Multiple-choice Questions

1 The average speed of a car is 35 km/h. If it travels at this speed for 45 minutes, what is the distance it has travelled?

A 0.78 km **B** 26.25 km

C 129 km **D** 467 km

2 S A car accelerates uniformly from 5 m/s to 13 m/s in 4.0 s. What is the acceleration of the car?

A 0.50 m/s^2 **B** 0.80 m/s^2

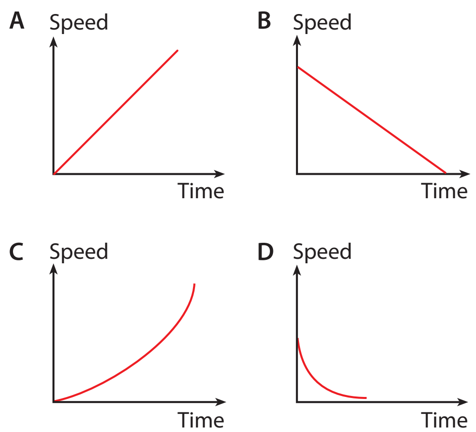
C 1.25 m/s^2 **D** 2.00 m/s^2

3 S A ball is thrown vertically upwards at 1.2 m/s. It decelerates uniformly at 10 m/s^2. What is the time taken for the ball to reach zero speed?

A 0.12 s **B** 2.4 s

C 6.0 s **D** 12 s

4 S Which speed–time graph shows the motion of an object which decelerates non-uniformly?



Section B: Short-answer and Structured Questions

1 A car travelled from town A to town B, and then to town C. It took 0.5 hour to travel 50 km from town A to town B. The car stopped for 0.25 hour in town B. Then it travelled another 30 km to town C in 1.25 hour.

Calculate the average speed of the car for the whole journey.

2 Figure 2.29 shows the speed–time graph for a car in motion.

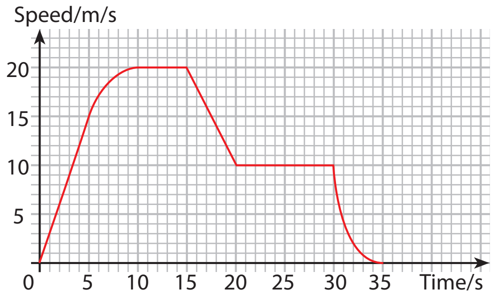


Figure 2.29

Describe the motion of the car between

(a) $t = 0$ s and $t = 10$ s;

(b) $t = 10$ s and $t = 15$ s;

(c) $t = 15$ s and $t = 20$ s;

(d) $t = 20$ s and $t = 30$ s;

(e) $t = 30$ s and $t = 35$ s.

3 S A train travels along a straight track from one station to another. Figure 2.30 shows how the speed of the train varies with time over the whole journey.

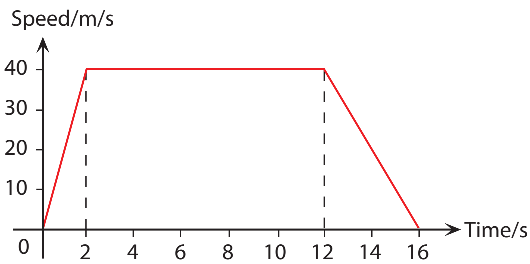


Figure 2.30

(a) State the time interval over which the train is decelerating.

(b) Determine the acceleration of the train.

(c) Determine

(i) the distance between the two stations;

(ii) the average speed of the train over the whole journey.

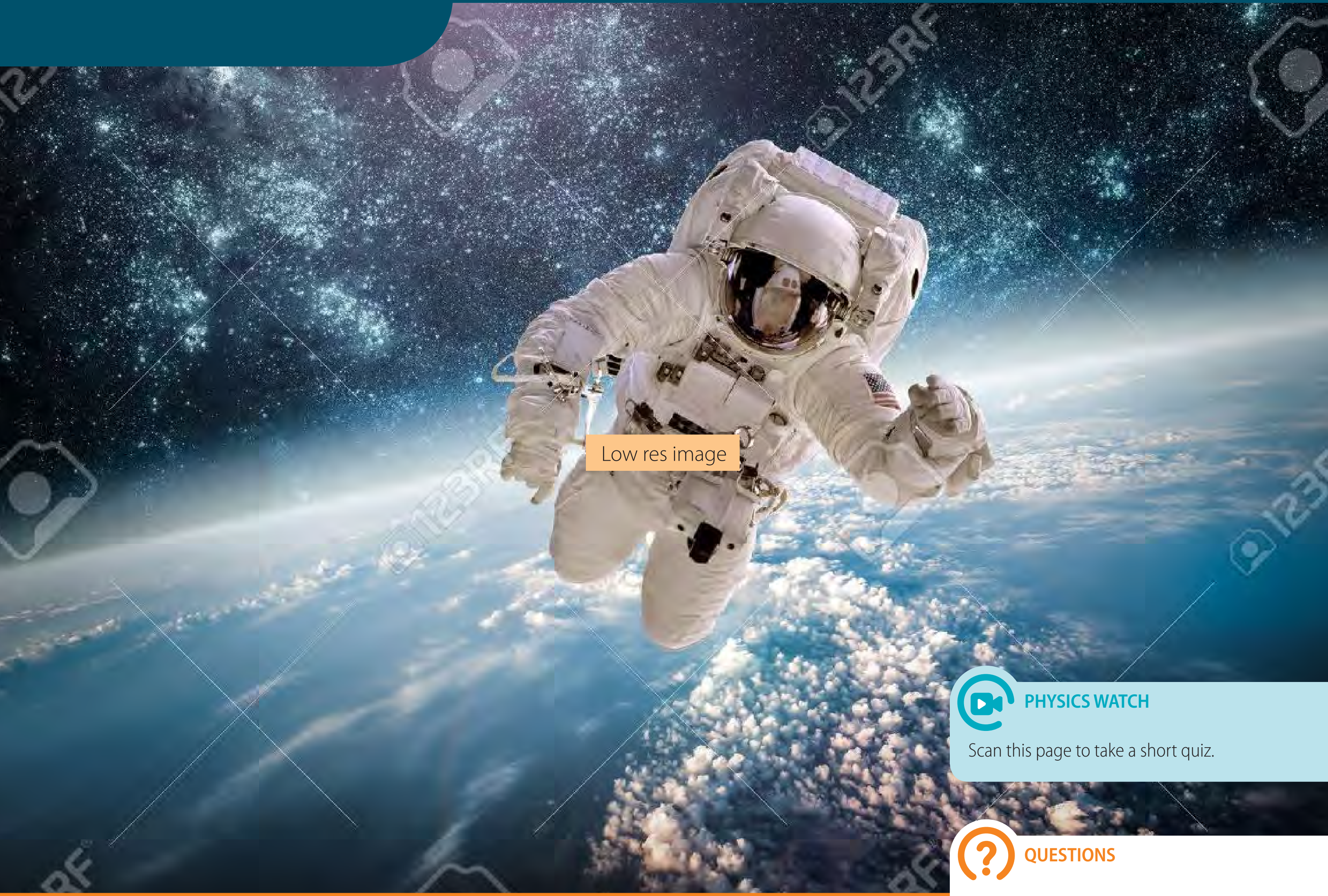
4 S A feather was released from rest in vacuum. It was then released from rest in air. In both situations, the feather was released from the same significant height.

(a) Compare and discuss the motion of the feather in vacuum and in air.

(b) Sketch the speed–time graphs of the motion of the feather in vacuum and in air.

CHAPTER 3

Mass, Weight and Density



PHYSICS WATCH

Scan this page to take a short quiz.

QUESTIONS

- Why does a spacecraft use a lot of energy to go into space?
- The astronaut in the photo is floating in space. Does the astronaut still have weight?
- Why is the astronaut able to bounce about easily on the Moon but not on the Earth?

A lot of energy is used to power a spacecraft when it is launched from the Earth towards space. Once in space, the spacecraft separates from its main engine and rocket boosters. It then fires its own engine to put it into orbit around the Earth. While in orbit, an astronaut sometimes leave the spacecraft to be out in open space.

When the spacecraft wants to land on the Moon, the engine is fired again to steer the spacecraft. Once on the Moon, the astronaut from the spacecraft can do some moonwalking. Unlike on the Earth, the astronaut is able to bounce about easily on the Moon.

3.1 Mass and Weight

In this section, you will learn the following:

- State what is meant by the term *mass* and *weight*.
- Ⓢ Describe, and use the concept of, weight as the effect of a gravitational field on a mass.
- Define *gravitational field strength*.
- Recall and use the equation $g = \frac{W}{m}$ and know that this is equivalent to the acceleration of free fall.
- Know that weights (and masses) may be compared using a balance.

Is mass the same as weight?

When we say that a person weighs 100 kilograms, we actually mean that the person has a body mass of 100 kilograms. When we buy a 5-kilogram bag of rice, we are buying a bag of rice that has a *mass* of 5 kilograms, not a bag of rice that *weighs* 5 kilograms.

In physics, weight and mass are two very different quantities. In everyday language, we often misuse the term *weight* when we mean *mass*. So, what is the difference between mass and weight?

What is mass?

Mass is a measure of the quantity of matter in an object at rest relative to the observer. Its SI unit is the **kilogram (kg)** .

The object has to be at rest when the observer measures the amount of matter in it. Why is this so?

Scientists have found that when an observer looks at an object moving at very high speeds (near to the speed of light), the observer sees that the object has a different mass from when it is stationary. However, such high speeds do not happen in everyday life. These observations take place in specially built laboratories that study small particles moving at very high speeds. The mass of an object is a fixed quantity under normal circumstances.

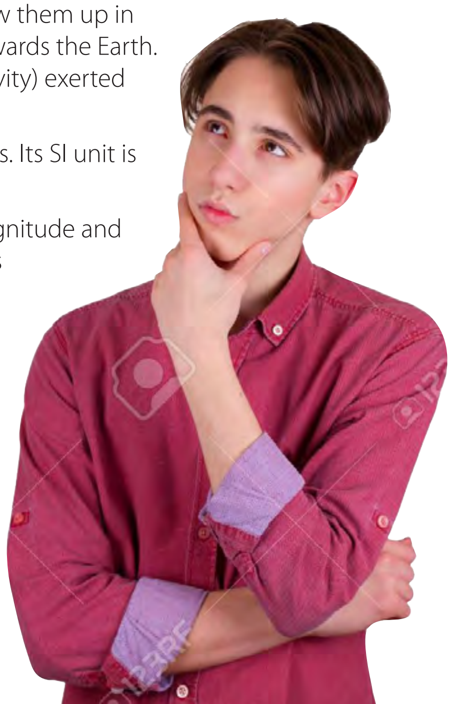
Thus, we can say that mass is a property of a body that does not change with its location or shape. The mass of a body depends on the number and composition of atoms and molecules that make up the body. It is a scalar quantity.

What is weight?

Do you know why objects fall to the ground after you throw them up in the air? This is because a force called weight pulls them towards the Earth. This force is the gravitational pull (gravitational force or gravity) exerted by the Earth.

Weight is the gravitational force on an object that has mass. Its SI unit is the **newton (N)**.

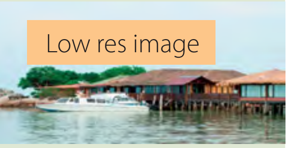
Since weight is a force, it is a vector quantity with both magnitude and direction. The direction of weight is downward, i.e., towards the centre of the Earth.



ENRICHMENT INFO

Tides

High tides and low tides are observed in places near the sea. Have you ever wondered what causes the tides?



(a) High tide

(b) Low tide

Figure 3.1 *Places near the sea experience tides*

Gravitational force of attraction exists between the Earth and the Moon. The high and low tides are the effects of the Moon's gravitational force on the Earth.

What is a gravitational field?

You have learnt earlier that the weight of an object with mass is due to the gravitational force acting on it. This weight is the effect of a gravitational field on a mass.

A **gravitational field** is a region of space in which a mass exert a force of attraction on another mass.

For example, the Earth with a huge mass has a gravitational field surrounding it. As such, any object within the Earth's gravitational field will experience a force exerted by the Earth on it. The gravitational force experienced is the strongest at the surface of the Earth. It gets weaker further away due to a decreasing gravitational field strength.

What is gravitational field strength?

The weight of an object depends on the strength of the gravitational force acting on it. For example, an object weighs less on the Moon than on the Earth. This is because the Moon's gravitational field strength is weaker than the Earth's gravitational field strength.

Gravitational field strength *g* is defined as the gravitational force per unit mass.

In equation form: $\boldsymbol{g = \frac{W}{m}}$ where g = gravitational field strength (in N/kg)

W = weight (in N)

m = mass of the object (in kg)

On the Earth, the gravitational field strength g is approximately 10 N/kg. This means that a 1-kg mass on the Earth's surface experiences a force of 10 N due to the Earth's gravitational field.

On the other hand, the same 1-kg mass on the Moon experiences a gravitational force of only 1.6 N. This is because the gravitational field strength on the Moon is 1.6 N/kg.

Imagine if we were to weigh an elephant on the Earth's surface and the Moon's surface (Figure 3.2). The elephant would weigh much more on the Earth's surface than on the Moon's surface even though its mass remains unchanged.

PHYSICS WATCH

Scan this page to explore a simulation on mass and weight.

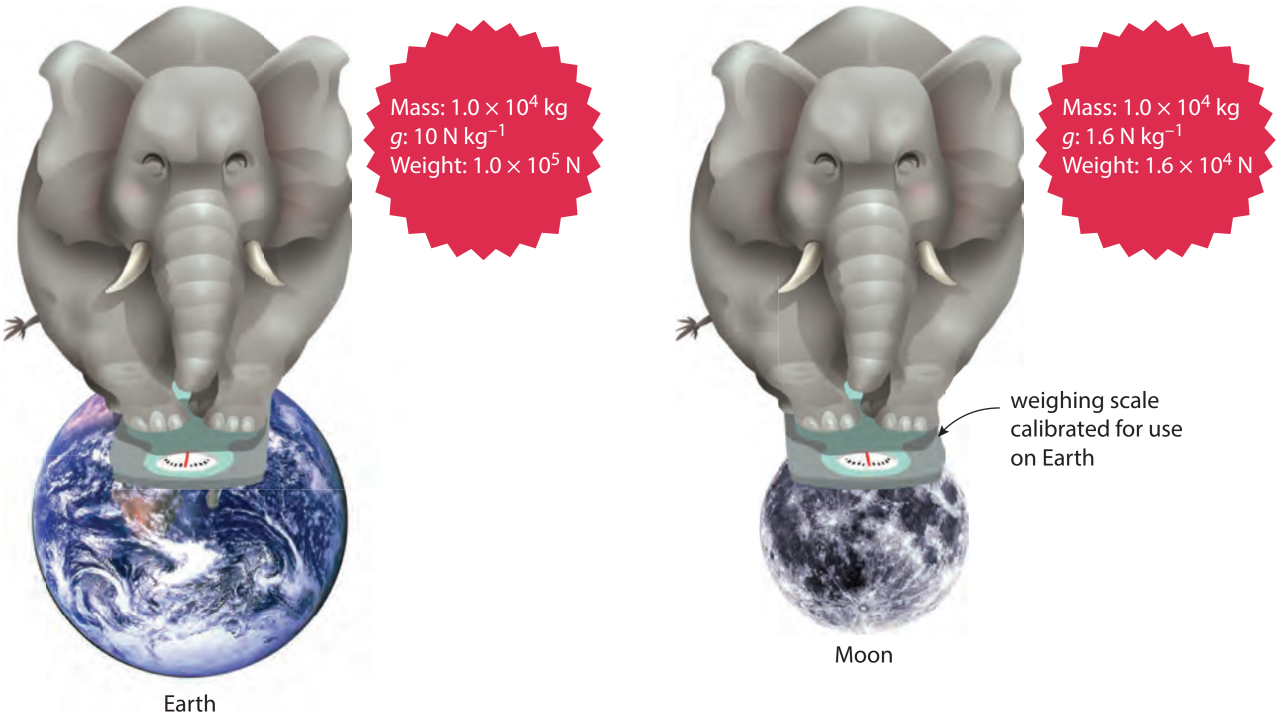


***Figure 3.2** The elephant 'loses' weight when it is on the Moon!*

How are mass and weight related?

From the equation $g = \frac{W}{m}$, we have $W = mg$. Thus, the weight or gravitational force W acting on an object is directly proportional to its mass m. For example, if we double the mass of the object, the weight or gravitational force acting on the object becomes doubled.

WORD ALERT

Directly proportional: to increase or decrease by the same number of times

Worked Example 3A

A mobile phone has a mass of 75 g. Calculate its weight if g is 10 N/kg.

Solution

Mass of mobile phone $m = 75 \text{ g} = 75 \times 10^{-3} \text{ kg} = 0.075 \text{ kg}$

Weight of mobile phone $W = mg = 0.075 \text{ kg} \times 10 \text{ N/kg} = 0.75 \text{ N}$

Gravitational field strength and acceleration due to gravity

On the Earth, the gravitational field strength g near its surface is 10 N/kg.

Therefore, the weight W (in N) of an object of mass m (in kg) is given by:

$W = mg$

$= m \times 10 \text{ N/kg}$ ------------- (1)

If the object were to free-fall under gravity without air resistance, we can find its acceleration using the equation:

$F = ma$ where F = resultant force (in N)

m = mass (in kg)

a = acceleration (in m/s^2)

LINK

You will learn more about the equation $F = ma$ in Chapter 4.

Consider an object of mass m (in kg) free-falling under gravity without air resistance. It is free-falling at an acceleration of $a = g = 10 \text{ m/s}^2$ due to its weight W (in N). So, we have

$F = ma$

$W = mg$

$= m \times 10 \text{ m/s}^2$ --------------- (2)

By equating equations (1) and (2), we have

$W = mg$

$= m \times 10 \text{ N/kg}$

$= m \times 10 \text{ m/s}^2$

Therefore, $10 \text{ N/kg} = 10 \text{ m/s}^2$. This shows that gravitational field strength near the Earth's surface $g = \frac{W}{m} = 10 \text{ N/kg}$ is equivalent to the acceleration of free fall $g = \frac{W}{m} = 10 \text{ m/s}^2$.

HELPFUL NOTES

The gravitational field strength $g = \frac{W}{m}$ is equivalent to the acceleration of free fall. However, the weight W of an object of mass m is $W = mg$ regardless of whether it is at rest or free-falling.

What do common weighing instruments measure?

Common weighing instruments, such as the electronic balance (Figure 3.3), spring balance and bathroom scale, actually measure the weight of an object, not its mass. These instruments, however, are calibrated to give readings in grams (g) or kilograms (kg).

Using these instruments, an object will have different mass readings at different gravitational field strengths. For example, if an astronaut steps on a bathroom scale on the Moon, the reading will be lower than the reading taken on the Earth. This is because the gravitational field strength on the Moon (1.6 N/kg) is less than that on the Earth (10 N/kg).

This means that a weighing scale calibrated for use on the Earth cannot be used on the Moon. The weighing scale has to be calibrated to the Moon's gravitational field strength in order to give accurate mass measurements on the Moon.

Figure 3.3 *The electronic balance is a commonly used laboratory instrument for measuring mass. In fact, electronic balances measure weight, but they are calibrated to give readings for mass.*

How is mass measured?

The mass of an object can be measured using a beam balance (Figure 3.4). Unlike a weighing scale, a beam balance does not have to be calibrated for different gravitational field strengths.

A beam balance compares the gravitational force acting on an object with that acting on standard masses. As both the object and the standard masses experience the same gravitational field strength, the mass reading taken for a given object, whether on the Earth or on the Moon, will be the same.

Table 3.1 shows how mass is different from weight.

Figure 3.4 *Simple beam balance used to measure mass*

Table 3.1 *Differences between mass and weight*

Mass	Weight
• An amount of matter	• A gravitational force
• A scalar quantity (i.e. has only magnitude)	• A vector quantity (i.e. has both magnitude and direction)
• SI unit: kilogram (kg)	• SI unit: newton (N)
• Independent of the gravitational field strength	• Dependent on the gravitational field strength
• Measured with a beam balance or a calibrated electronic balance	• Measured with a spring balance

Worked Example 3B

The acceleration of free fall on the Moon is 1.6 m/s^2. The acceleration of free fall on the Earth is 10 m/s^2. A rock has a mass of 10 kg on the Earth. Calculate the weight of the rock on

(a) the Earth; **(b)** the Moon.

Solution

We know that

- the mass of the rock does not change whether on the Earth or on the Moon;
- weight = mass × acceleration of free fall.

(a) Therefore, the weight of the rock on the Earth = 10 kg × 10 m/s^2 = 100 N

(b) The weight of the rock on the Moon = 10 kg × 1.6 m/s^2 = 16 N

(Note: 1 kg m/s^2 = 1 N)

QUICK CHECK

As a satellite is launched from the Earth into space, its weight decreases while its mass remains unchanged.

True or false?

Let's Practise 3.1

1 Give four differences between mass and weight.

2 Why is the mass of a body not affected by changes in the physical environment such as location?

3 The Moon has a gravitational field strength one-sixth that of the Earth's. If a person has a mass of 60 kg on the Earth, how much will he weigh on the Moon?

4 The gravitational field strength of Jupiter is 22.9 N/kg. An astronaut weighs 1200 N on the Earth. What will his weight be on Jupiter? Assume the gravitational field strength of the Earth is 10 N/kg.

5 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

Exercise 3A, pp. XX–XX

3.2 Density

In this section, you will learn the following:

- Define *density* and recall and use the equation $\rho = \frac{m}{V}$.
- Describe how to determine the density of a liquid and certain solids.
- Determine whether an object floats based on density data.
- S Determine whether one liquid will float on another liquid based on density data.

What is density?

When we talk about density, we are talking about how much mass is packed into a given space.

The **density** of a substance is defined as its mass per unit volume.

In some cases, density can be used to identify substances. For example, the density of pure gold is 19 300 kg/m^3. If the density of a gold ring is not 19 300 kg/m^3, then it is not made of pure gold — it must have some impurities in it.

To calculate the density of a substance, we need to know its mass m and its volume V. Density ρ (Greek letter 'rho', pronounced 'row') is given by

$\boldsymbol{\rho = \frac{m}{V}}$ where ρ = density

m = mass of the object

V = volume of the object

The SI unit of density is the **kilogram per cubic metre (kg/m³)**.

If mass is measured in kilograms (kg) and volume in cubic metres (m^3), the unit of density would be the SI unit. However, if mass is measured in grams (g) and volume in cubic centimetres (cm^3), the unit of density would be gram per cubic centimetre (g/cm^3).

As most objects we handle daily have relatively small masses and volumes, the unit g/cm^3 is more commonly used. The densities of some common substances are shown in Table 3.2.

HELPFUL NOTES

To convert density values from g/cm^3 to kg/m^3, we simply multiply them by 1000.

Table 3.2 *Densities of common substances*

Substance	Density /g/cm^3
Gases	
Dry air	0.00123
Oxygen	0.00143
Liquids	
Turpentine	0.87
Oil	0.92
Pure water	1
Seawater	1.025
Mercury	13.6
Solids	
Polystyrene	0.016
Cork	0.24
Pine wood	0.5
Ice	0.917
Glass	2.5
Iron	7.874
Gold	19.3

Substances that float on water have lower densities than water. Substances that sink in water have higher densities than water.

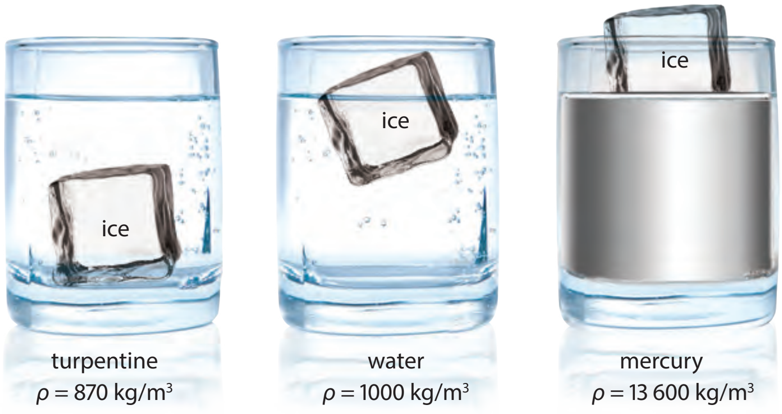


Figure 3.5 *Ice cubes placed in three different liquids. The density of the liquid determines whether the ice cube floats or sinks.*

ENRICHMENT ACTIVITY

Place a solid cube of modelling clay in water and watch it sink to the bottom of the tank of water.

Now, if you have a much smaller cube of the same modelling clay, will it float or sink in the water?

If it sinks again, can you think of a way to make it float?

Why does a heavy steel ship float?

A small iron ball sinks in water, but a large and heavy ship (Figure 3.6) floats! Why?

A large ship is an object that is made up of more than one material. In addition to steel, it contains a large volume of air in the various rooms and cabins. Therefore, we will have to consider the average density of the ship. The average density of an object is calculated by dividing its total mass by its total volume.

For example, a ship of mass 7.68×10^7 kg is 268 m long, 32 m wide and 25 m high. What is the average density of the ship?

Assuming a cuboidal shape,

the volume of the ship = 268 m × 32 m × 25 m = 214 400 m^3;

the mass of the ship = 7.68 × 107 kg.

Therefore, the average density of the ship:

$$\text{Average density} = \frac{\text{mass}}{\text{volume}} = \frac{7.68 \times 10^7 \text{ kg}}{214\,400 \text{ m}^3} = 358 \text{ kg/m}^3$$

The average density of the ship is actually less than the density of seawater, which is about 1025 kg/m^3. Therefore, the ship is able to float!

ENRICHMENT INFO

Submarine

A submarine is an interesting watercraft that can sink, float or be at rest at any position in the ocean. How is it possible?

The feature that gives a submarine of a fixed size or volume this capability is the special tanks known as ballast tanks. These ballast tanks can be filled with different amounts of air or water to vary the total mass of the submarine.

Figure 3.6 *Why does a large and heavy ship float, while an iron ball sinks?*

Let's Investigate 3A

Objective

To determine the density of a liquid

Apparatus

Burette, beaker, electronic balance, retort stand

Procedure

1. Find the mass m_1 of a dry, clean beaker.
2. Run a volume V of liquid from the burette into the beaker (Figure 3.7).
3. Find the mass m_2 of the beaker and the liquid.

Precaution

When reading the volume of the liquid, make sure that your eyes are level with the base of the meniscus of the liquid.

Calculation

If the masses are measured in g and the volume in cm³, then the density ρ of the liquid is

$$\rho = \frac{m_2 - m_1}{V}\ \text{g/cm}^3 = \frac{m_2 - m_1}{V} \times 1000\ \text{kg/m}^3.$$

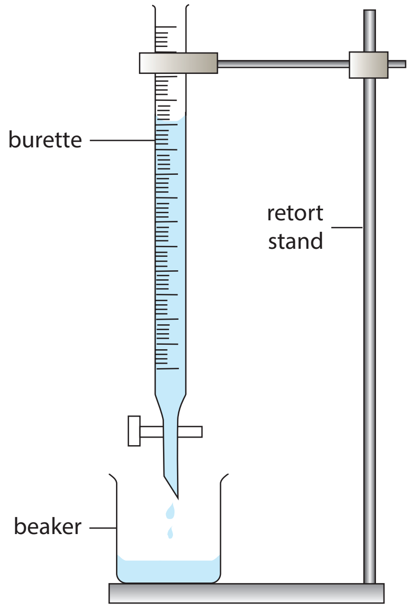


Figure 3.7

Let's Investigate 3B

Objective

To determine the density of regular objects (Figure 3.8)

Apparatus

Vernier callipers, metre rule, electronic balance

Procedure

1. Find the mass m using the electronic balance.
2. Determine the volume V by taking appropriate measurements and then calculating the volume using the following formulae:
   (a) Cuboid — measure the length l, breadth b and height h

   $V = l \times b \times h$

   (b) Cylinder — measure the diameter d and length l

   $V = \frac{\pi d^2}{4} \times l$

   (c) Sphere — measure the diameter d

   $V = \left(\frac{4}{3}\right)\pi\left(\frac{d}{2}\right)^3$

Precaution

Check the instruments used for zero error, and avoid parallax error when taking readings.

Calculation

If the mass of the object is in g and the volume in cm³, then density ρ of the object $= \frac{m}{V}\ \text{g/cm}^3 = \frac{m}{V} \times 1000\ \text{kg/m}^3$.

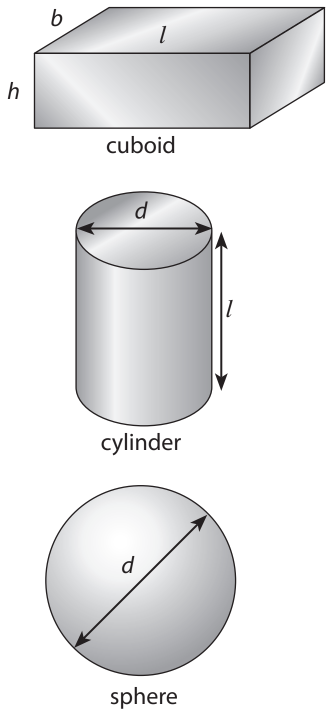


Figure 3.8

QUICK CHECK

If a block of metal is broken into two equal parts, the density of each part is half the density of the original metal block.

True or false?

Let's Investigate 3C

Objective
To determine the density of irregularly shaped objects that sink in liquid (such as a glass stopper in water)

Apparatus
Measuring cylinder, glass stopper, string, electronic balance, water, small towel, scissors

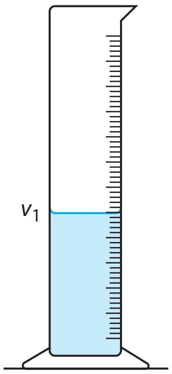


Figure 3.9

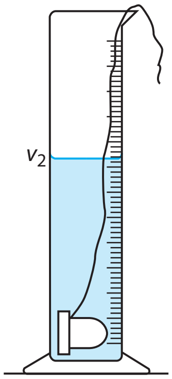


Figure 3.10

Procedure
1. Measure the mass *m* of the glass stopper using the electronic balance.
2. Fill the measuring cylinder with water to about one-third of its depth. Note the volume reading V_1 (Figure 3.9).
3. Tie a piece of string to the glass stopper and then lower it gently into the water. Note the new volume reading V_2 (Figure 3.10).
4. Determine the volume of the glass stopper, given by $V_2 - V_1$.
5. Remove the glass stopper from the measuring cylinder and dry it with the towel.
6. Repeat steps 2 to 5 twice with different values of V_1 and obtain the corresponding values of V_2 and $(V_2 - V_1)$.
7. Determine the volume *V* of the glass stopper by taking the average value of the three sets of data for $(V_2 - V_1)$.

Precaution
Check the instruments used for zero error, and avoid parallax error when taking readings.

Calculation
If the mass of the glass stopper is in g and the volume in cm^3,
then density ρ of the glass stopper $= \frac{m}{V}$ g/cm^3 $= \frac{m}{V} \times 1000$ kg/m^3.

LINK
Recall what zero error and parallax error are from Chapter 1.

LINK PWB
Practical 3A, pp. XX–XX

ENRICHMENT THINK

Can balloons carry you up into the sky?

In 1982, Mr. Larry Walters from USA, attached 45 helium weather balloons to a lawn chair, sat on it and soared into the sky.

He reportedly reached a height of 5000 m before bursting the balloons one by one with a pellet gun. On his way down, the balloons' loose cables got entangled with power lines. This resulted in a 20-minute blackout in Long Beach, USA! After his misadventure, Larry was nicknamed the "Lawn Chair Pilot".

Based on what you have learnt about density, can you explain why balloons can lift a person into the sky? Can they lift a person to outer space? Why?

WORD ALERT

Conversely: on the other hand, in the opposite way

Worked Example 3C

A cube of side 2.0 cm has a density of 6.0 g/cm³. A hole of volume 1.0 cm³ is drilled into the cube. The hole is filled up with a certain material of density 5.0 g/cm³. Calculate the density of this composite cube in **(a)** g/cm³; **(b)** kg/m³.

Solution

(a) Mass of 1.0 cm³ of the material of density 5.0 g/cm³ $= 5.0\text{ g/cm}^3 \times 1.0\text{ cm}^3 = 5.0\text{ g}$

Volume of cube after a hole of 1.0 cm³ is drilled $= (2.0 \times 2.0 \times 2.0)\text{ cm}^3 - 1.0\text{ cm}^3$

$= 7.0\text{ cm}^3$

Mass of cube after a hole of 1.0 cm³ is drilled $= 6.0\text{ g/cm}^3 \times 7.0\text{ cm}^3 = 42.0\text{ g}$

$$\therefore \text{Density of composite cube} = \frac{\text{mass of composite cube}}{\text{volume of composite cube}}$$

$$= \frac{(42.0 + 5.0)\text{ g}}{(7.0 + 1.0)\text{ cm}^3}$$

$$= 5.9\text{ g/cm}^3$$

(b) To convert to kg/m³, recall that $1\text{ kg} = 1000\text{ g}$ (or $1\text{ g} = 10^{-3}\text{ kg}$)

Since 1 m = 100 cm,

$1\text{ m}^3 = (100)^3\text{ cm}^3 = 10^6\text{ cm}^3$ (or $1\text{ cm}^3 = 10^{-6}\text{ m}^3$).

Therefore, $1\text{ g/cm}^3 = \dfrac{1\text{ g}}{1\text{ cm}^3} = \dfrac{10^{-3}\text{ kg}}{10^{-6}\text{ m}^3} = 1000\text{ kg/m}^3$.

Thus, $5.9\text{ g/cm}^3 = 5.9 \times 10^3\text{ kg/m}^3$.

Worked Example 3D

In an experiment, a solid material of unknown density is placed in three different liquids. Table 3.3 shows the results of the experiment.

Table 3.3

Liquid	Density of liquid/(kg/m³)	Observation
Mercury	14 000	The object floats
Seawater	1100	The object floats
Paraffin	700	The object sinks

Which of the following shows the density of the object?

A Exactly 700 kg/m³

B Between 700 kg/m³ and 1100 kg/m³

C Exactly 1100 kg/m³

D Between 1100 kg/m³ and 14 000 kg/m³

Explain your choice.

Solution

B. For any solid material to float in a liquid, the density of the material must be lower than the density of the liquid. Conversely, for any solid material to sink in a liquid, its density must be higher than the density of the liquid. Based on the density values of the three different liquids, this means that the density of the solid material is lower than 1100 kg/m³ and higher than 700 kg/m³.

Worked Example 3E

A physics teacher showed some students a simple experiment. She prepared some water, glycerine and mercury in three small separate beakers. The teacher poured the water into a measuring cylinder, followed by glycerine and then mercury. The students observed that the three liquids did not mix but instead settled into three distinct layers in a certain order.
Table 3.4 shows the densities of the three liquids.

Table 3.4

Liquid	Density of liquid/(kg/m^3)
Mercury	13 600
Glycerin	1260
Water	1000

Which of the following shows the correct order of the three liquids starting from the bottom of the measuring cylinder?

A Water, glycerine, mercury
B Glycerine, water, mercury
C Mercury, glycerine, water
D Mercury, water, glycerine

Explain your choice.

Solution
C. When any two liquids that do not mix are placed in the same container, the liquid with the lower density will float on top of the liquid with the higher density. Based on the density values of the three immiscible liquids, mercury with the highest density will sink to the bottom of the measuring cylinder. Water with the lowest density will float to the top. Glycerine, with a density lower than mercury and higher than water, will form the middle layer.

WORD ALERT

Immiscible: do not mix when put together

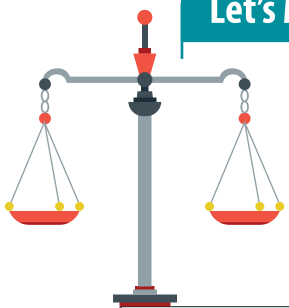
Let's Practise 3.2

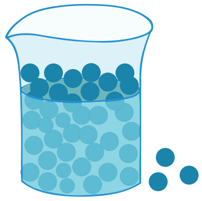
1 Define *density* and state its SI unit.
2 Given that the density of water is 1000 kg/m^3, what is the mass of 1.0 cm^3 of water in grams?
3 How would you measure the density of an irregularly shaped object that sinks in water?
4 The mass of a measuring cylinder is 60.0 g. When 30 cm^3 of olive oil is poured into it, the total mass is 87.6 g. What is the density of olive oil in g/cm^3?
5 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK

Exercises 3B–3C, pp. XX-XX
Exercise 3D Let's Reflect, p. XX

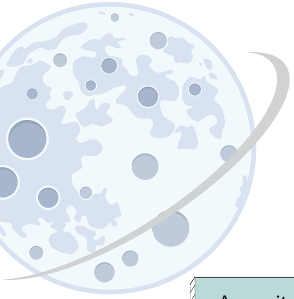
Let's Map It





MASS m
(SI unit: kg)

- MASS m — is defined as → A measure of the quantity of matter in an object at rest relative to the observer
- MASS m — values may be compared using →
  - Electronic balance
  - Beam balance
- MASS m — is related to → WEIGHT W and DENSITY ρ

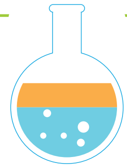


WEIGHT W
(SI unit: N)

- Weight — values may be compared using → Electronic balance; Beam balance
- WEIGHT W — is defined as → A gravitational force on an object that has mass
  - → $W = m \times g$
  - where → Gravitational field strength g is the force per unit mass.
  - which is equivalent to → Acceleration of free fall g
- WEIGHT W — can be described as → S The effect of a gravitational field on a mass

DENSITY ρ
(SI unit: kg/m³)

- DENSITY ρ — is defined as → Mass per unit volume
  - → $\rho = \frac{m}{V}$
  - → Based on density data, we can determine
    - whether an object floats;
    - S whether one liquid will float on another liquid, given the two liquids do not mix.



Let's Review

Section A: Multiple-choice Questions

1 Which of the following statements is correct?
 A The mass of an object can be measured with a spring balance.
 B The weight of an object can be measured with a beam balance.
 C The mass of an object does not change with location.
 D The weight of an object can never change.

2 A rock on the Moon has a mass of 0.5 kg. It is brought to the Earth, where the gravitational field strength is stronger. On the Earth, the rock will have
 A less mass and less weight.
 B less mass and the same weight.
 C the same mass and the same weight.
 D the same mass and more weight.

3 A measuring cylinder contains 20 cm^3 of water. When ten identical steel balls are immersed in the water, the water level rises to 50 cm^3. If one ball has a mass of 27 g, what is the density of the steel in g/cm^3?
 A 0.9
 B 8.1
 C 9.0
 D 13.5

Section B: Short-answer and Structured Questions

1 Explain the following observations:
 (a) The mass of a piece of rock, measured using a beam balance, is the same on the Earth and on the Moon.
 (b) The weight of the same piece of rock, measured using a spring balance, is different on the Earth and on the Moon.

2 A breakfast cereal packet carries the following label:
This package is sold by weight, not volume. Some settling of the contents may have occurred during transport.
If settling occurs, what changes, if any, will occur to the
 (a) mass of the contents;
 (b) weight of the contents;
 (c) volume of the contents;
 (d) density of the contents?

3 **(a)** A boy made a model ship with a mass of 1.1 kg and a volume of 900 cm^3. Will it float on water? (Take the density of water to be 1000 kg/m^3.)
 (b) A piece of gold has a mass of 10.0 g and a density of 19.3 g/cm^3.
  (i) What is the volume occupied by the piece of gold?
  (ii) When the piece of gold is placed in a beaker of mercury of density 13 600 kg/m^3, explain whether it will float or sink?

4 Figure 3.11 shows a rectangular solid block of dimensions 20 cm by 10 cm by 15 cm. It has a cylindrical hole bored at its centre.

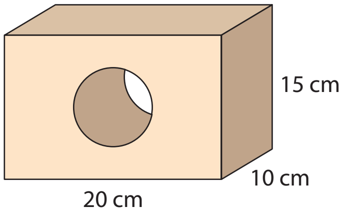


Figure 3.11

The mass of the block is 14.9 kg, and it is made of a material that has a density of 5 g/cm^3.
 (a) What is the mass of the block in gram?
 (b) What is the volume of the block before the cylindrical hole is bored at its centre?
 (c) What is the cross-sectional area of the hole in cm^2?

5 S Two liquids A and B are poured into a tall beaker half-filled with water. It is observed that three distinct layers are formed with the water layer in between liquid A above it and liquid B below it.
 (a) Is the density of liquid A greater than water?
 (b) If the density of water is 1000 kg/m^3, what can you deduce about the densities of liquid A and liquid B?

CHAPTER

4 Forces

PHYSICS WATCH

Scan this page to watch a clip what keeps a kite flying in the air.

QUESTIONS

- A main force is responsible to enable the *wau bulan* to fly. Where does this force come from?
- What other forces are acting on the kite when it is flying in the air?
- A big *wau bulan* will not fly when the wind is not strong enough. Why?

This man is getting ready to fly his *wau bulan*. *Wau bulan* is a type of kite traditionally flown in Kelantan, a state in Malaysia. The lower part of the kite is shaped like a crescent moon. That is how the kite got its name — *bulan* means *moon* in Malay.

A typical *wau bulan* measures 2.5 m in width and 3.5 m in height. Its frame is made of bamboo. A large *wau bulan* can be very heavy and would need several people to launch it into the sky. When there is a strong wind, the *wau bulan* is lifted up. The forces acting on it enable it to fly as high as 500 m in the air. To control the height and path of the kite, a few people on the ground hold and pull the string attached to it.

4.1 Forces

In this section, you will learn the following:

- Know the effects of forces.
- Sketch, plot and interpret load–extension graphs and describe the associated experimental procedures.
- S Define *spring constant*.
- S Recall and use the equation $k = \frac{F}{x}$.
- S Define and use the term *limit of proportionality*, and identify this point on a load–extension graph.

LINK

Recall what you have learnt in Chapter 2 about the acceleration of free fall, *g*.

What are some effects of forces?

You have learnt that gravitational force causes objects close to the Earth's surface to fall with the acceleration of free fall, *g* (about 9.8 m/s²). This is one effect of a force. Figure 4.1 shows some other effects of forces.

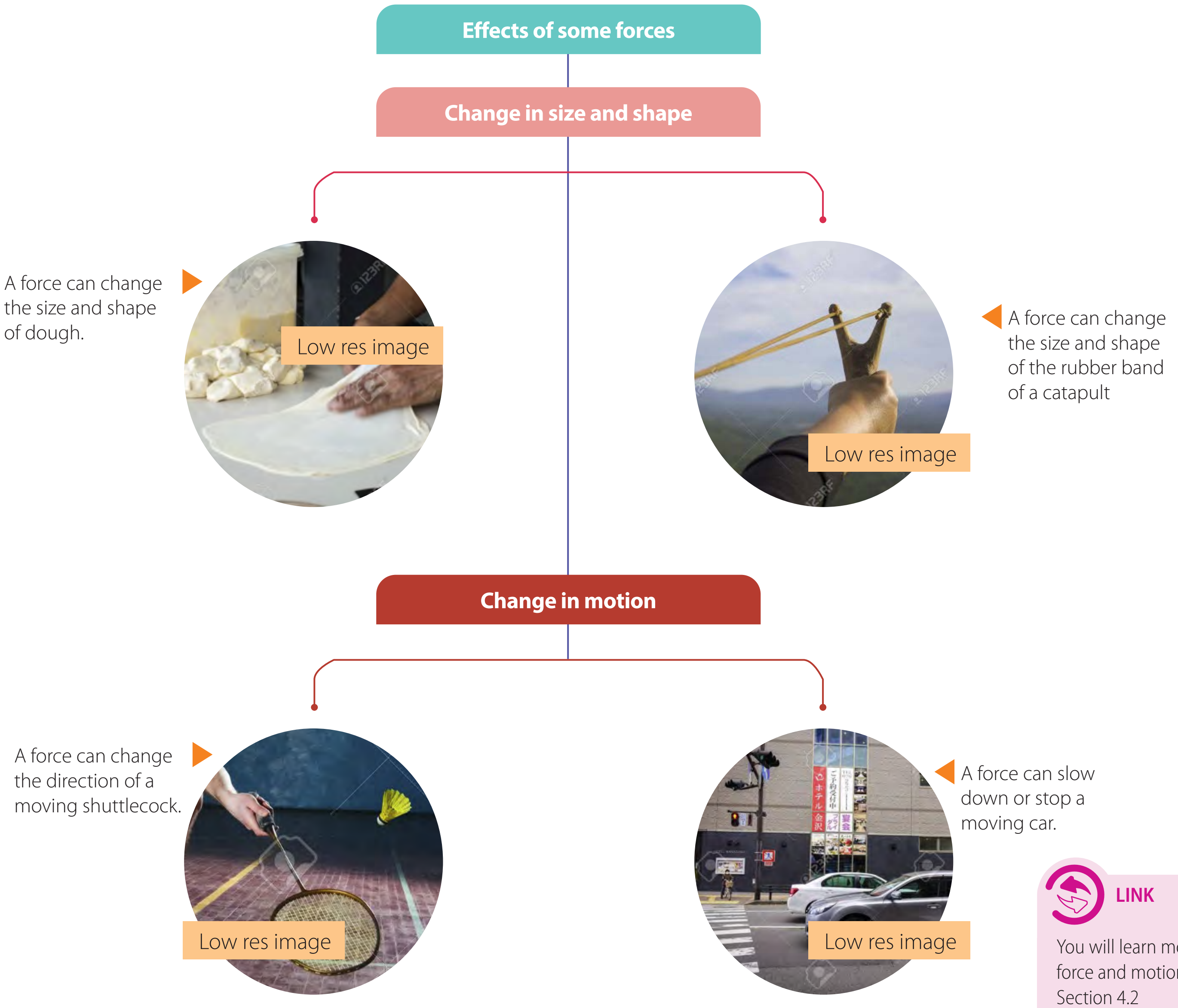


Figure 4.1 *Effects of some forces*

LINK

You will learn more about force and motion in Section 4.2

How can we study the effects of forces?

How much force is needed to cause an object to move? How much force can an object endure before it breaks? To find out, we need to study the effects of forces.

A simple study can be done to find out the effects of different loads on an elastic solid. An elastic solid is an object that changes in size and shape when a force is applied, and returns to its original size and shape when the force is removed. Examples of elastic solids are rubber bands and springs.

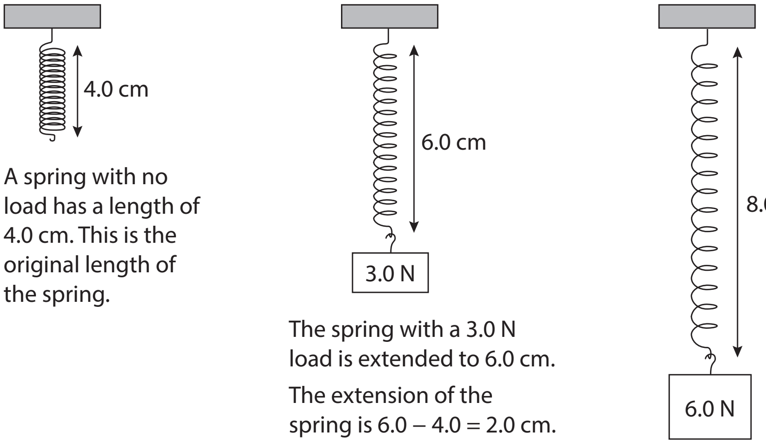
WORD ALERT

Endure: withstand, cope with

Extends: stretches

Load–extension graph

Figure 4.2 shows the effects of different loads on a spring. When a load is attached to the spring, the spring extends. We can calculate the extension of the spring by taking the difference between the extended length and the original length.



A spring with no load has a length of 4.0 cm. This is the original length of the spring.

The spring with a 3.0 N load is extended to 6.0 cm.

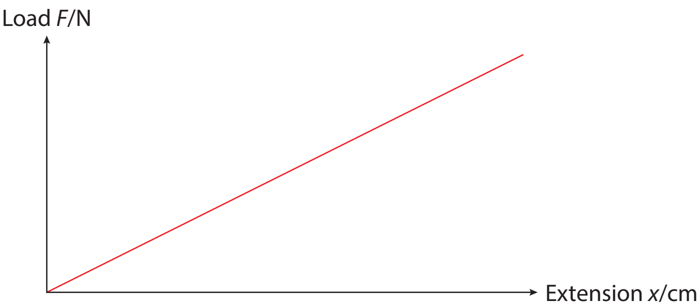
The extension of the spring is 6.0 – 4.0 = 2.0 cm.

The spring with a 6.0 N load is extended to 8.0 cm.

The extension of the spring is 8.0 – 4.0 = 4.0 cm.

Figure 4.2 *The extension of the spring depends on the amount of force applied.*

From Figure 4.2, the extension of the spring is doubled from 2.0 cm to 4.0 cm when the load is doubled from 3.0 N to 6.0 N. The load, i.e. the force applied, is directly proportional to the extension.



When the load is not too heavy, the load–extension graph shows a straight line passing through the origin (i.e. load is directly proportional to extension).

Figure 4.3 *A sketch of load–extension graph for an elastic solid*

HELPFUL NOTES

The size of extension of a spring when pulled depends on the type of material it is made of. However, the force applied is always proportional to the extension.

We can plot a **load–extension graph** (Figure 4.3) to show the relationship between the force and the extension of an elastic solid. This relationship can help us determine the magnitude of an unknown force on an elastic solid.

Let's Investigate 4A

Objective
To investigate the relationship between force and the extension of a spring

Materials
Metre rule, spring, standard 1 N loads, hanger, retort stand

Procedure
1. Set up the experiment as shown in Figure 4.4.
2. Measure the length l_0 of the spring without any load, i.e. force $F = 0$ N. Position your eye correctly to avoid parallax error. Record this length using Table 4.1.
3. Attach a 1 N load to the hanger on the spring. Measure the new length l of the spring and record this length for $F = 1$ N.
4. By adding 1 N loads, measure and record the new lengths of the spring for F values of 2 N, 3 N, 4 N and 5 N.
5. After you have recorded the length of the spring for $F = 5$ N, remove a 1 N load. You now have a 4 N force applied on the spring. The spring should return to the length you have recorded for $F = 4$ N.
6. Remove another 1 N load so that $F = 3$ N, and check the length of the spring. Repeat this for F equals 2 N, 1 N and 0 N.
7. Calculate the extension $x = l - l_0$ for each row of Table 4.1.
8. Plot a graph of F/N (y-axis) against x/mm (x-axis).

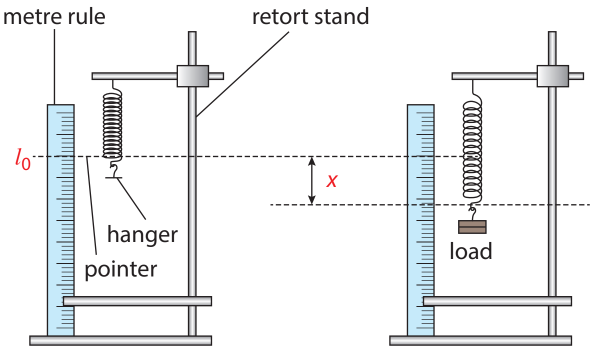


***Figure 4.4** Experimental set-up to investigate the extension of a spring*

Table 4.1

F/N	0	1	2	3	4	5
l/mm	l_0					
x/mm	0					

Discussion and conclusion
By using the data recorded in Table 4.1, we can plot the load–extension graph for the spring. The graph will look similar to the one in Figure 4.3 on page 50.

The load–extension graph for the spring shows that the force applied is directly proportional to the extension of the spring.

We can measure the extension of the spring when a load of unknown weight is attached to it, and plot a graph. We can then use the graph to determine the unknown weight.

LINK
Recall what you have learnt in Chapter 1 about how to avoid parallax error.

HELPFUL NOTES
We can conduct similar experiments to obtain the load–extension graphs for other elastic solids. Instead of the spring, we can use elastic bands or polythene strips.

LINK
PWB
Practical 4A, pp. XX–XX

QUICK CHECK

The load–extension graph of spring A has a steeper gradient than that of spring B. Spring A is more elastic than spring B.

True or false?

Worked Example 4A

A student measures the length of a spring. He then attaches different loads to the spring. He measures the length of the spring for each load. Table 4.2 shows his results.

(a) Plot the load–extension graph.

(b) Deduce the relationship between force and extension based on the graph.

(c) The student attaches a load of unknown weight to the spring and measures the length of the spring. The length is found to be 21.0 cm. What is the weight of this load?

Table 4.2

Load *F*/N	Length/cm
0	16.0
1.0	18.0
2.0	20.0
3.0	22.2
4.0	23.8
5.0	26.0

Solution

(a) To plot the load–extension graph, we need to calculate the extension for each load. Table 4.3 shows the values obtained.

Table 4.3

Load *F*/N	Extension *x*/cm
0	16.0 – 16.0 = 0
1.0	18.0 – 16.0 = 2.0
2.0	20.0 – 16.0 = 4.0
3.0	22.2 – 16.0 = 6.2
4.0	23.8 – 16.0 = 7.8
5.0	26.0 – 16.0 = 10.0

Figure 4.5 shows the graph of Load *F*/N against Extension *x*/cm.

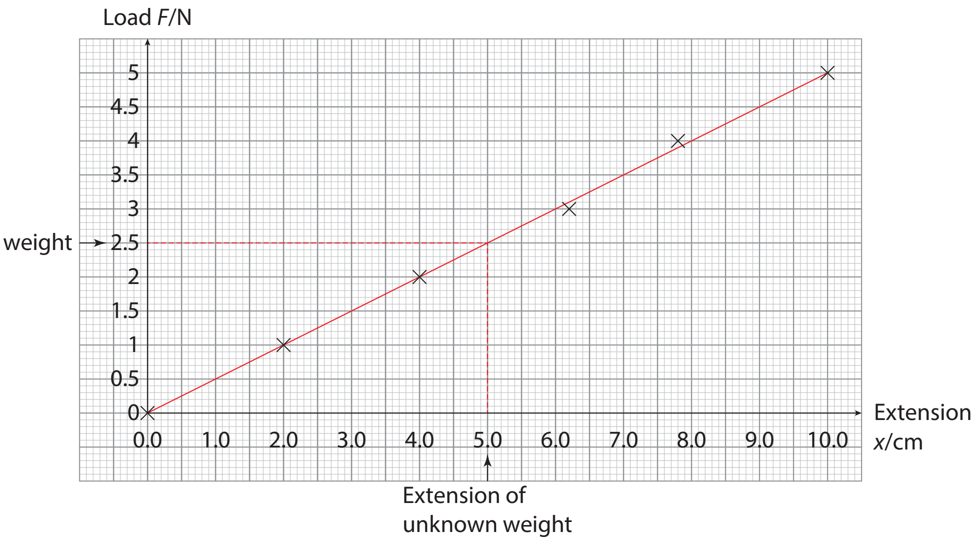


Figure 4.5

(b) The weight of the load is the force acting on the spring. The load–extension graph is a straight line passing through the origin. This shows that force is directly proportional to the extension for the spring.

(c) For the unknown weight, the extension $x = 21.0 - 16.0 = 5.0$ cm

From the graph, when the extension is 5.0 cm, the load is 2.5 N.

Spring constant and limit of proportionality

Recall that the load–extension graph for a spring is a straight line with a positive gradient. This means that for any point along the graph, the ratio of load F to extension x always gives the same value, i.e. a constant. This constant is called the spring constant and is given by

$$\boldsymbol{k = \frac{F}{x}}$$ where k = spring constant
F = force
x = extension

The **spring constant** is defined as the force per unit extension.

The unit for k depends on the units for force F and extension x. When F is in N and x is in cm, the unit for k is N/cm. Similarly, when F is in N and x is in mm, the unit for k is N/mm. Since the SI unit for length is m, and force is N, the SI unit for the spring constant is **newton per metre (N/m)**.

Refer to Worked Example 4A on page 52. What is the spring constant of the spring?

We can take any values of force F and extension x to calculate the spring constant.

So, for F = 5 N and x = 10 cm,

$$k = \frac{F}{x} = \frac{5}{10} = 0.5 \text{ N/cm}$$

However, the force or load is proportional to the extension only when value of F is not too large. There is a point beyond which the extension is no longer directly proportional to the load. This point is called the **limit of proportionality** as shown in Figure 4.6.

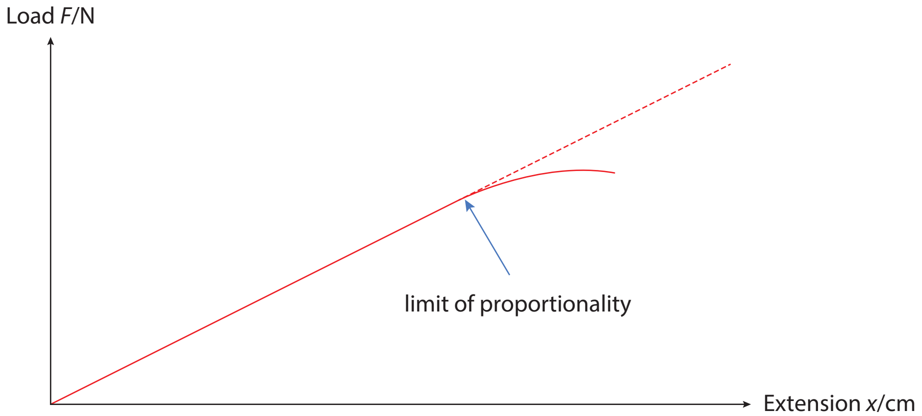


Figure 4.6 *Load–extension graph showing the limit of proportionality*

ENRICHMENT THINK

When a spring is stretched within its limit of proportionality, will it always return to its original size and shape? What happens when it is stretched beyond its limit of proportionality?

Worked Example 4B

Two girls want to weigh a watermelon, but they do not have a kitchen scale. So they use a spring and a 1 kg bag of sugar to measure. When suspended, the bag of sugar stretches the spring by 50 mm, while the watermelon stretches the spring by 75 mm. Assuming that the extension of the watermelon is within the limit of proportionality,

(a) calculate the spring constant of the spring;

(b) calculate the weight of the watermelon.

(Take g = 10 N/kg.)

Solution

Weight of 1 kg bag of sugar = 1 × 10 = 10 N

(a) Spring constant $k = \frac{F}{x} = \frac{10 \text{ N}}{50 \text{ mm}} = 0.2$ N/mm

(b) Weight $W = kx$ = 0.2 N/mm × 75 mm = 15 N

WORD ALERT

Suspended: made to hang freely

Let's Practise 4.1

1 A student measured the length of a spring which was found to be 25.0 cm. She then attached an 8 N weight to the spring. She measured the new length, which was found to be 29.0 cm.

(a) Calculate the extension of the spring.

(b) The student decided to plot a load–extension graph for the spring. She repeated the step above to obtain the extension of the spring for the following weights: 2 N, 4 N, 6 N and 10 N. Sketch a graph to show what her load–extension graph would look like.

(c) S Calculate the spring constant of the spring.

(d) S Using your answer in **(c)**, calculate the extension of the spring when the load is 14 N.

(e) S The student decided to increase the weight on the spring up to 14 N. Table 4.4 shows her results.

(i) Use the table to plot the load–extension graph.

(ii) Explain why the extension of the spring for $F = 14$ N was different from the calculated value in **(d)**.

Table 4.4

***F*/N**	0	2	4	6	8	10	12	13	14
***x*/cm**	0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0

LINK TWB

Exercise 4A, pp. XX–XX

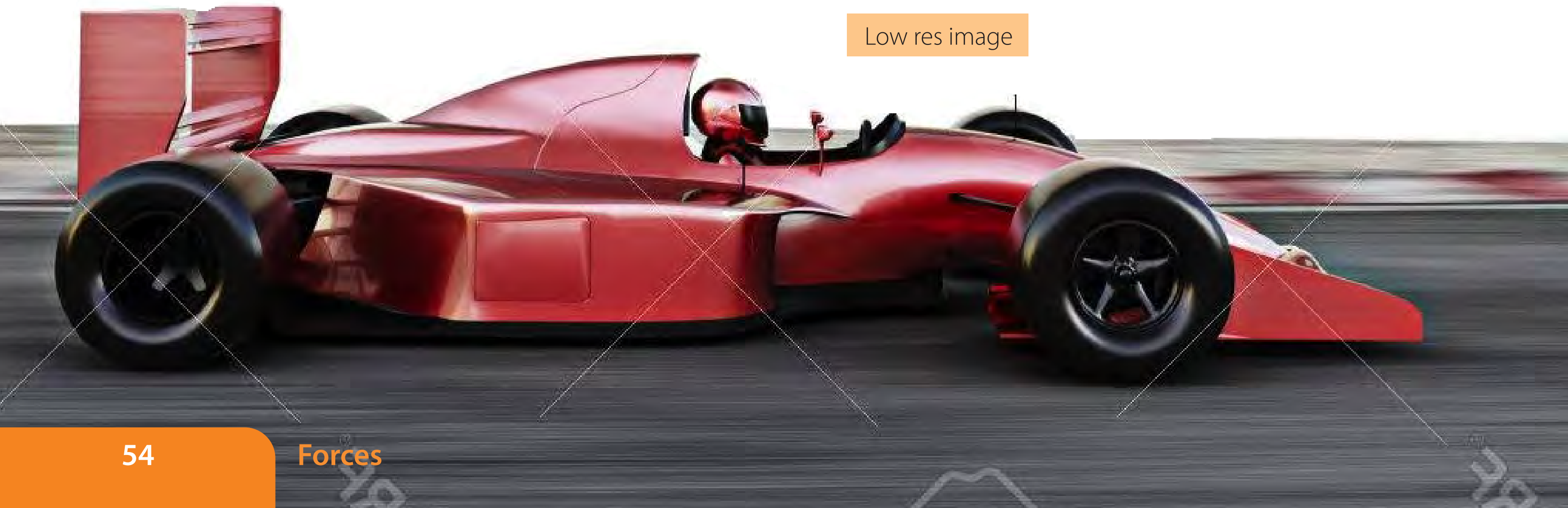
2 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

4.2 Forces and Motion

In this section, you will learn the following:

- Determine the resultant force.
- State the effects of a resultant force.
- Know that an object either remains at rest or continues in a straight line at constant speed unless acted on by a resultant force.
- Describe *solid friction*.
- Know that friction acts on an object moving through a liquid or a gas.
- S Recall and use the equation $F = ma$ and know that the force and the acceleration are in the same direction.
- S Describe, qualitatively, motion in a circular path due to a force perpendicular to the motion.

Low res image



How can we determine the resultant force on an object?

A force is a vector quantity with both magnitude and direction. When more than one force acts on an object, we need to consider the direction of each force in order to determine the resultant force. Figure 4.7 shows how to determine the resultant force on a ball with two or more forces acting along the same straight line.

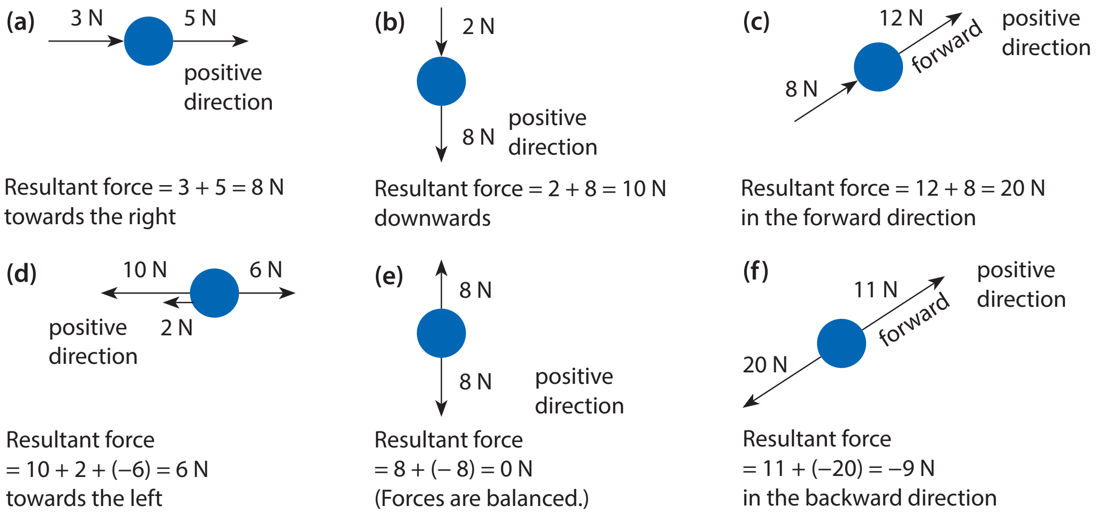


Figure 4.7 *Calculating the resultant force acting on a ball*

LINK

Recall what you have learnt in Chapter 1 about how to add vectors.

HELPFUL NOTES

When determining the resultant force for forces acting in a straight line, remember to assign one direction as positive. The opposite direction will be negative. The sign of the resultant force, after adding the forces, will tell you the direction of the resultant force.

How does a resultant force affect motion?

Imagine holding a ball in your hands. What happens when you throw the ball upwards? What is the resultant force on the ball? It is the gravitational force acting downwards. This downward resultant force causes all objects near the Earth to accelerate towards the Earth. It also changes the direction of an object moving upwards so that it falls back downwards (Figure 4.8).

A resultant force may change the velocity of an object by changing its direction of motion or its speed.

What happens when the resultant force is zero?

Balanced forces

When the forces acting on an object are balanced, the resultant force acting on the object is zero. The motion of the object with zero resultant force depends on the initial state of the object.

- If an object is at rest, it will remain at rest (stationary) until it is acted on by a resultant force.
- If an object is moving with zero resultant force, it will continue to move in a straight line with constant speed until it is acted on by a resultant force.

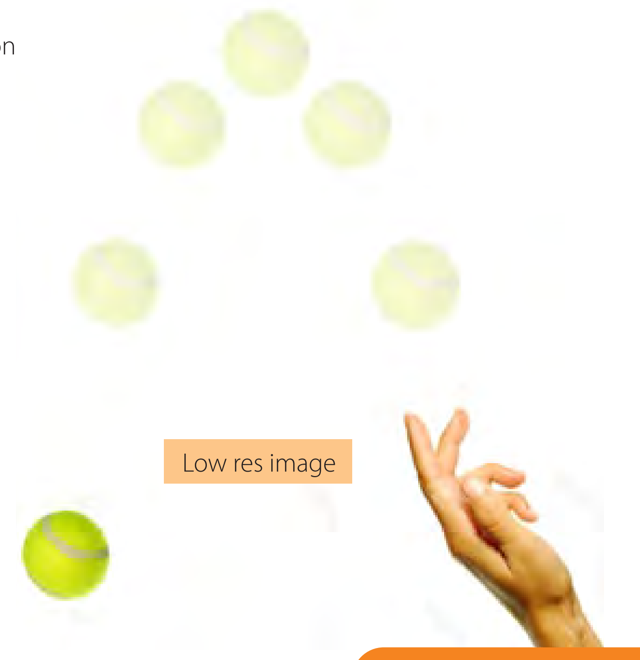


Figure 4.8 *The ball falls back downwards after being thrown upwards due to the gravitational force acting on it.*

PHYSICS WATCH

Scan this page to explore the effect of resultant force on motion.

HELPFUL NOTES

Do you notice that N is equivalent to kg m/s^2? In fact, this is the definition of the newton: 1 N is the resultant force acting on an object of 1 kg mass when the object accelerates at 1 m/s^2.

Can an object move at constant speed in a straight line when the resultant force is zero? A trolley must be constantly pushed or it will stop moving. This is because a force that opposes motion, is always present between two moving surfaces. When the pushing force on the trolley is zero, this opposing force becomes the new resultant force which stops the trolley.

Unbalanced forces

A resultant force may change the velocity of an object by changing its direction of motion or its speed.

When the forces acting on an object are unbalanced, the resultant force acting on the object is not zero. The resultant force causes the object to move in a different direction, or to accelerate or decelerate.

S When a resultant force causes an object to move, the object will accelerate in the direction of the resultant force.

The resultant force F acting on an object of mass m is related to the acceleration of the object by the following equation:

$\boldsymbol{F = ma}$ where F = force (in N)

m = mass (in kg)

a = acceleration (in m/s^2)

Worked Example 4C

Figure 4.9 shows the forces acting on an object at rest. The mass of the object is 20 kg.

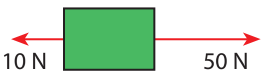


Figure 4.9

(a) Calculate the resultant force on the object.

(b) What effect does this resultant force have on the object?

(c) S What is the velocity of the object after 2 s?

Solution

(a) Let the right direction be positive.

Resultant force = 50 N + (–10 N) = 40 N towards the right

(b) The resultant force changes the velocity of the object. It causes the object to accelerate.

(c) S Using $F = ma$, $a = \frac{40}{20} = 2$ m/s^2 towards the right

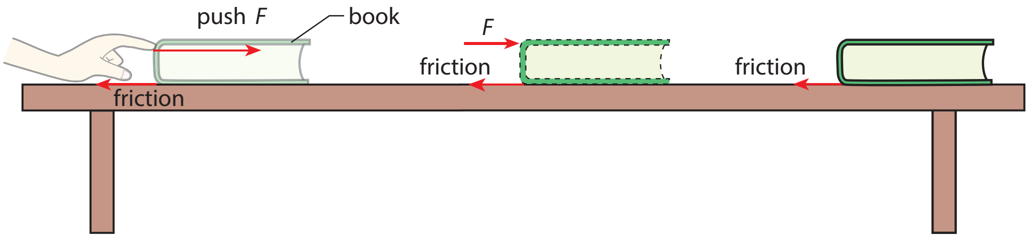
Since $a = \frac{\text{change in velocity}}{\text{time taken}} = \frac{v - 0}{2}$

The velocity v of the object after 2 s = 2 × a = 2 × 2 = 4 m/s towards the right.

What are the effects of friction?

Friction is a force that impedes motion.

Solid friction is the type of friction that occurs when two solid surfaces are in contact with or slide against each other. In Figure 4.10, we see that a force greater than the friction must be applied so that there is a non-zero resultant force to make the object move. The object will stop if we remove the applied force.



① To make the book move across the table, we apply a force that is greater than the friction between the table and the book. The resultant force towards the right makes the book move in the same direction.

② Once the book is moving, we apply a force of the same magnitude as the friction such that the resultant force is zero.

③ When we stop applying a force, the resultant force is only the friction, towards the left. As the direction of the resultant force is opposite to the motion of the book, the book stops moving.

Figure 4.10 *Friction acts in the opposite direction to motion*

Friction between two moving surfaces produces heating. For example, our hands feel warm when we rub them together.

Friction does not only oppose motion between solid surfaces. Objects moving through a liquid or a gas experience friction too. A swimmer is slowed by friction between the water and her body. A car moving on a road, or an aeroplane flying in the air experiences air resistance, which opposes the motion of the vehicle.

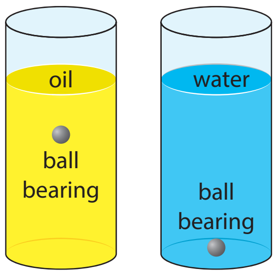
Friction is a resistive force because it acts in the opposite direction to motion.

In liquids and gases, friction is usually called **drag** (Figure 4.11).

Drag

In liquids

- A ball bearing falls more slowly in oil than in air or in water as there is more drag acting on the ball bearing falling in oil.



In air

- The parachutist slows down when she opens the parachute as there is air resistance opposing her downward motion.

Figure 4.11 *Motion through a liquid or a gas will experience drag.*

WORD ALERT

Impedes: slows down or prevents something

Resistive: opposing, acting against

PHYSICS WATCH

Scan this page to watch a clip on the forces acting on a skydiver.

QUICK CHECK

An object cannot move when the resultant force acting on it is zero.

True or false?

How does a force cause an object to move in a circular path?

An object moving in a circular path with a constant speed is shown in Figure 4.12. An object in a circular path has the following properties:

- The direction of its velocity is changing all the time.
- A non-zero resultant force acts on it to keep the object in a circular path.
- The direction of the force changes as the object moves.
- The force is perpendicular to the motion of the object.

Figure 4.12 shows the directions of the velocity and force when the object is at positions (1), (2), (3) and (4). At each position, the perpendicular force pulls the moving object towards the centre of the circle.

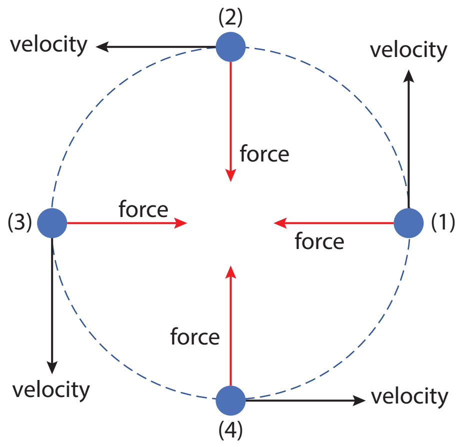


Figure 4.12 *Motion in a circular path is due to a force perpendicular to the motion.*

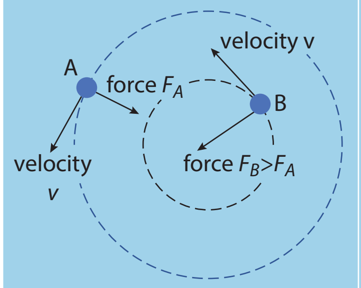
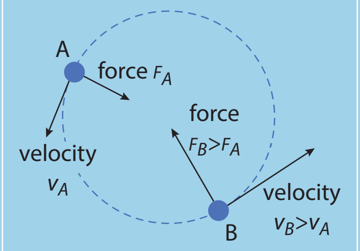
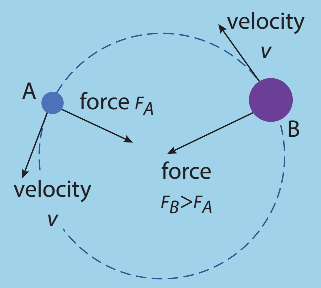
WORD ALERT

Perpendicular: at a 90° angle to a given line, plane or surface

Force and circular motion

The magnitude of the force required to keep an object moving in a circular path depends on three quantities — mass of the object, speed of the object and the radius of the circular path. Table 4.5 shows how force is related to these three quantities for an object in circular motion.

Table 4.5 *Force, mass, speed and radius of circular path for an object in circular motion*

Constant mass and speed	Constant mass and radius	Constant speed and radius
 *Figure 4.13*	 *Figure 4.14*	 *Figure 4.15*
Figure 4.13 shows the forces on two objects of the same mass and moving with the same speed. The force on object B is greater. As a result, the radius of the circular path for object B is smaller.	Figure 4.14 shows two objects with the same mass and moving in the same circular path. The force on object B is greater. As a result, the speed of object B is greater than the speed of object A.	In Figure 4.15, the mass of object B is greater than that of object A. For object B to move at the same speed as object A and in the same circle, the force on object B must be greater than that on object A.
With mass and speed of the object constant, the radius of the circular path decreases if the force increases.	**With mass of the object and radius of circular path constant, the speed of the object increases if the force increases.**	**To keep speed of the object and radius of circular path constant, an increased mass of the object requires an increased force.**

Let's Practise 4.2

1 Read each of the following descriptions carefully. State if it is true or false. Correct any description which is false.
   (a) The resultant force on a moving object is zero. The object stops moving.
   (b) The resultant force on an object is zero. The object remains at rest.
   (c) An object is moving to the right. A resultant force towards the right acts on it. The object slows down.
   (d) An object is moving downwards. An upward force with magnitude equals to the weight of the object acts on the object. The resultant force is zero and the object falls at constant speed.
   (e) Friction acts in the direction opposite to the motion of an object.
   (f) Friction can cause heating.
   (g) There is no friction in liquids or gases.
   (h) S Acceleration = force × mass
   (i) S A resultant force on a moving object is perpendicular to its velocity. This force has no effect on the motion of the object.
   (j) S An object is moving in a circular path. The resultant force on the object increases. If the object continues moving at the same speed, it must continue to move with a smaller radius.

2 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

TWB LINK

Exercise 4B, pp. XX–XX

4.3 Turning Effect of Forces

In this section, you will learn the following:

- Describe the moment of a force and give everyday examples.
- Define the moment of a force as moment = force × perpendicular distance from the pivot; recall and use this equation.
- Apply the principle of moments to situations with one force on each side of the pivot.
- S Apply the principle of moments to other situations, including those with more than one force on each side of the pivot.
- State that, when there is no resultant force and no resultant moment, an object is in equilibrium.
- S Describe an experiment to demonstrate that there is no resultant moment on an object in equilibrium.

What is the moment of a force?

A force acting on an object can cause the object to turn. This effect is known as the *turning effect of a force*. An example of this can be seen when we open a door. We apply a force to swing the door about its hinge (Figure 4.16).

The turning effect can be large or small. How can we measure the turning effect of a force?

Figure 4.16 *Turning effect depends on where the force is applied*

The turning effect is measured by a physical quantity known as *moment of a force*.

In Figure 4.17, we observe that objects turn about a fixed location, called the **pivot**.

Figure 4.17 *Using the turning effect of a force in our daily lives*

To produce a turning effect, the force applied must be at a distance from the pivot.

If the force is applied at the pivot, there is no turning effect. This would be like trying to open a door by pushing at the hinge — the door would not open.

Figure 4.18 shows a simplified diagram of a door being pulled. The hinge is the pivot and the force F applied is shown by an arrow. Distance d is the perpendicular distance from the pivot to the line of action of the force.

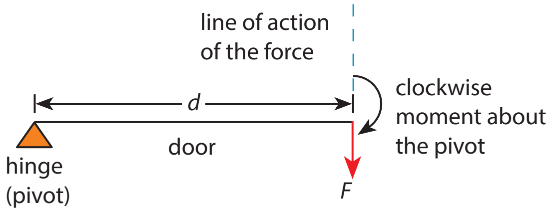


Figure 4.18 *Simplified diagram of a door being pulled*

Moment of a force is defined as the product of the force and the perpendicular distance from the pivot.

Its SI unit is **newton metre (N m)**.

Moment of a force = $F \times d$

where F = force (in N)

d = perpendicular distance from the pivot (in m)

Moment of a force is a vector quantity.
Its direction can be clockwise (Figure 4.18) or anti-clockwise (Figure 4.19).

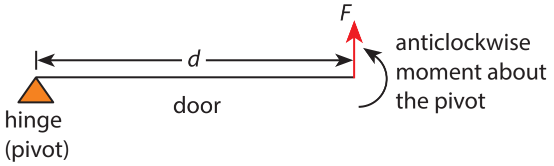


Figure 4.19 *Simplified diagram of a door being pushed*

If the force applied is 5 N and the perpendicular distance is 0.3 m, the moment of a force

- in Figure 4.18 = 5 × 0.3 = 1.5 N m clockwise;
- in Figure 4.19 = 5 × 0.3 = 1.5 N m anticlockwise.

Worked Example 4D

The minimum moment to open a door is 20.5 N m. The door must be opened with a force of 50 N at the handle. Calculate the minimum distance of the handle from the hinge.

Solution

Given: Moment = 20.5 N m , minimum force F = 50 N

Moment = Fd

$$\therefore d = \frac{\text{moment}}{F} = \frac{20.5\text{ N m}}{50\text{ N}} = 0.41\text{ m}$$

The handle should be at least 0.41 m away from the hinge.

What is the principle of moment?

Figure 4.20 shows two forces F_L and F_R acting on a steering wheel. The pivot is at the centre of the wheel. What is the resultant moment?

The moments are both in the anticlockwise direction.

Moment of $F_L = 4\ \text{N} \times 12\ \text{cm} = 48\ \text{N cm}$

Moment of $F_R = 4\ \text{N} \times 12\ \text{cm} = 48\ \text{N cm}$

We can find the resultant moment by adding the moments together.

Resultant moment = 48 N cm + 48 N cm = 96 N cm

The wheel turns in the anti-clockwise direction.

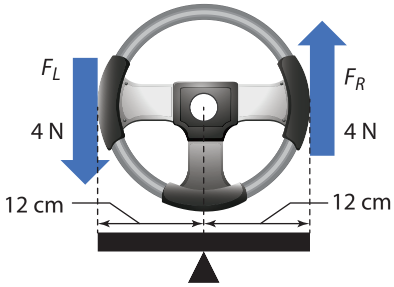


Figure 4.20 *Two forces on a steering wheel acting in opposite directions*

Suppose the force F_R is **reversed** so that it is in the same direction as F_L (Figure 4.21). What effect does the reversing of force have on the resultant moment?

Now, the moments are both in opposite directions.

Moment of F_L = 48 N cm anticlockwise

Moment of F_R = 48 N cm clockwise

Take the anti-clockwise direction to be positive.

Resultant moment = 48 N cm + (−48) N cm = 0 N cm

There is no resultant moment. The wheel does not turn.

When the total clockwise moment is equal to the total anticlockwise moment, there is no resultant turning effect about a pivot. This is the **principle of moments**.

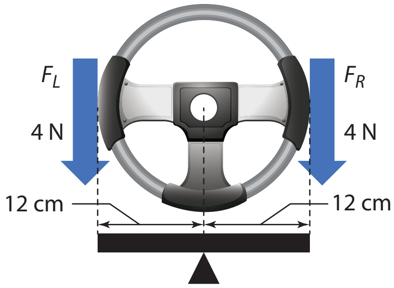


Figure 4.21 *Two forces on a steering wheel acting in the same direction*

WORD ALERT

Reversed: made to go in the opposite way

Worked Example 4E

A man holds a stiff fishing rod with two hands. A 30 N fish hangs at one end. Figure 4.22 shows the positions of the man's hands and the fish on the rod, with the right hand as the pivot and the left hand applying a force F. The rod is horizontal, stationary and very light, such that the effect of its weight is negligible. Calculate the force F.

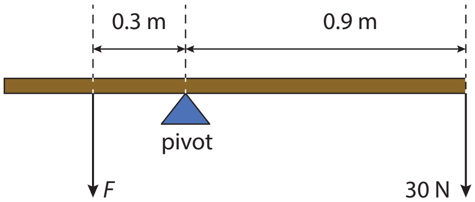


Figure 4.22

Solution

Clockwise moment of the fish's weight = 30 N × 0.9 m = 27 N m

Anticlockwise moment of F = $F \times 0.3$ m = 0.3 F N m

Using the principle of moments,

(0.3 m)F = 27 N m

$$F = \frac{27\ \text{N m}}{0.3\ \text{m}} = 90\ \text{N}$$

QUICK CHECK

When calculating moments, we can assign the clockwise direction as positive.

True or false?

S

Worked Example 4F

Figure 4.23 shows a similar diagram as Figure 4.22 in Worked Example 4E. This time, consider the pivot to be at the left hand and the force *F* applied using the right hand. Calculate the force *F*.

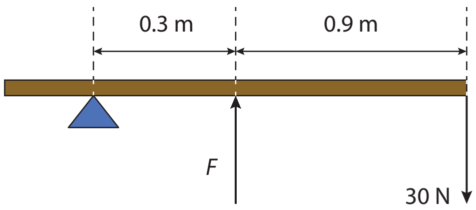


Figure 4.23

Solution

Perpendicular distance of the fish from the pivot = 0.9 m + 0.3 m = 1.2 m

Clockwise moment of the fish's weight

= 30 N × 1.2 m = 36 N m

Anticlockwise moment of $F = F \times 0.3$ m = 0.3 F N m

Using the principle of moments,

(0.3 m)F = 36 N m

$$F = \frac{36 \text{ N m}}{0.3 \text{ m}} = 120 \text{ N}$$

Worked Example 4G

Figure 4.24 shows a hand winch. Figure 4.25 shows a simplified diagram of the hand winch. The hand winch is used to move a load of 3000 N. Calculate the minimum force required to turn the drum.

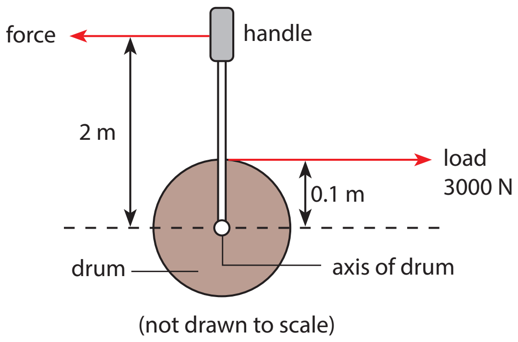


Figure 4.24

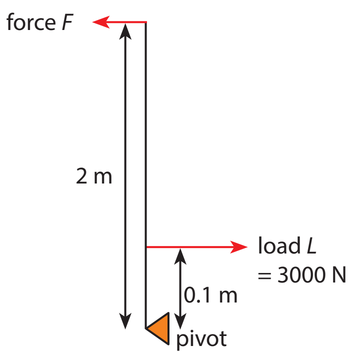


Figure 4.25

Solution

Clockwise moment of load L about the pivot = 3000 N × 0.1 m = 300 N m

Anticlockwise moment of force F about the pivot = F × 2 m = 2F N m

Taking anticlockwise direction to be positive, resultant moment = (2F – 300) N m

To turn the drum, resultant moment > 0.

(2 m)F – (300 N m) > 0

$$F > \frac{300 \text{ N m}}{2 \text{ m}} > 150 \text{ N}$$

The minimum force required to turn the drum is 150 N.

What happens when an object is in equilibrium?

When there is no resultant force, an object either remains at rest or moves at a constant speed along the same straight line.

When there is no resultant moment, the total anti-clockwise moments equal the total clockwise moments, and the object does not turn.

When there is no resultant force and no resultant moment, an object is in equilibrium.

PHYSICS WATCH

Scan this page to explore the principle of moments.

Let's Investigate 4B

Objective

To demonstrate that there is no resultant moment on an object in equilibrium

Materials

Metre rule, optical pin, retort stand, 50 g and 100 g masses, split cork, plasticine, thread

Procedure

1. Set up the experiment as shown in Figure 4.26.
2. Balance the metre rule at the 50 cm mark using an optical pin as shown.
3. Check that the metre rule can rotate freely about the pin in both directions.
4. Balance the metre rule about the pivot by fixing some plasticine to the end that tends to move up. The attached plasticine remains a part of the metre rule for the rest of the experiment.

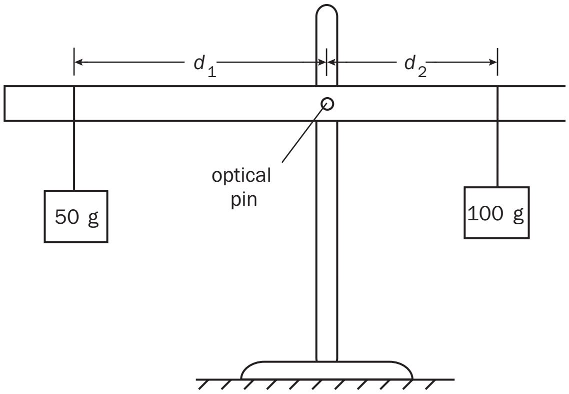


Figure 4.26

5. Using a loop of thread, hang mass $m_1 = 50$ g on one side of the rule at a distance $d_1 = 45.0$ cm from the pivot.
6. Balance the rule horizontally by hanging mass $m_2 = 100$ g on the other side. Measure and record the distance d_2 from the mass m_2 to the pivot (Figure 4.26) in Table 4.6.
7. Repeat steps 5 and 6, using 40.0 cm, 35.0 cm, 30.0 cm, and 25.0 cm for d_1.
8. Calculate the anticlockwise moment, clockwise moment and resultant moment at each distance. Remember that the force exerted by m_1 is about 0.5 N and that exerted by m_2 is about 1 N.

Table 4.6

d_1/cm	Anticlockwise moment/N cm	d_2/cm	Clockwise moment/N cm	Resultant moment/N cm
45.0				
40.0				
35.0				
30.0				
25.0				

Observation and conclusion

From Table 4.6, we observe that whenever the anticlockwise moment is equal to the clockwise moment, the resultant moment is zero. The metre rule does not turn and stays in equilibrium.

LINK

Practical 4B, pp. XX–XX

Let's Practise 4.3

1 Write the word equation for moment of a force.

2 What are the conditions for an object to be in equilibrium?

3 A uniform metre rule is balanced at its midpoint as shown in Figure 4.27.

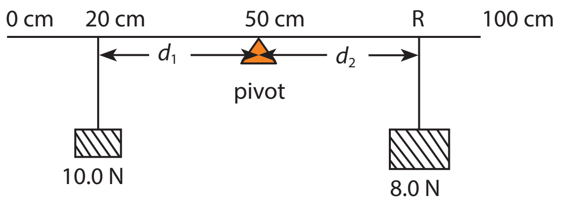


Figure 4.27

(a) Calculate distance d_1.

(b) Calculate the moment of 10.0 N weight.

(c) The ruler is in equilibrium. Find the position R.

4 S Figure 4.28 shows the forces on a pole AB lying horizontally on the ground. Calculate the minimum vertical force *F*, needed to lift the pole.

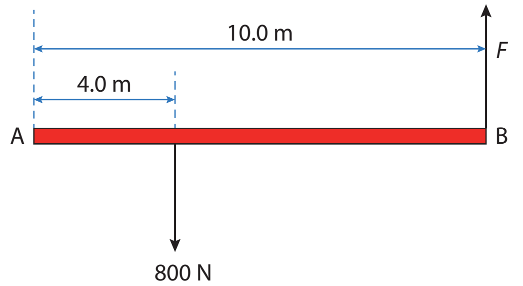


Figure 4.28

5 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

Exercise 4C, pp. XX–XX

4.4 Centre of Gravity

In this section, you will learn the following:

- State what is meant by *centre of gravity*.
- Describe an experiment to determine the position of the centre of gravity of an irregularly-shaped plane lamina.
- Describe qualitatively the effect of the position of the centre of gravity on the stability of simple objects.

What is centre of gravity?

At which point can you balance a uniform metre rule on the tip of your finger?

If you place your finger at the 30 cm mark or the 60 cm mark, the metre rule will topple. Gravitational force causes the metre rule to turn and fall.

What happens if you place your finger at the 50 cm mark?

WORD ALERT A-Z

Topple: to lose balance and fall down

When your finger is at the 50 cm mark, the metre rule balances perfectly (Figure 4.29). Why is this so?

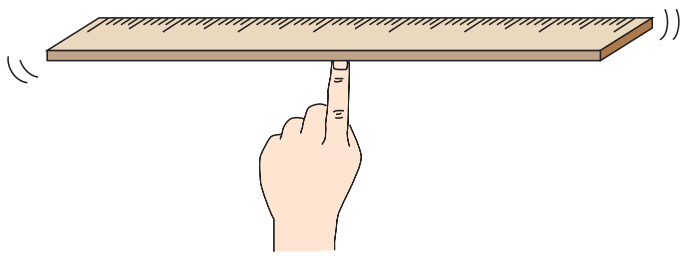


Figure 4.29 Balancing a metre rule on the tip of a finger

Gravitational forces pull at every part of an object. The resultant gravitational force on the object is its weight. It acts through a point known as the centre of gravity.

The **centre of gravity** of an object is the point through which the weight of the object acts.

When the object is balanced at its centre of gravity, the object does not turn because there is no resultant moment of its weight. The object does not move because the support exerts an upward force to balance its weight (Figure 4.30). The object is said to be in equilibrium.

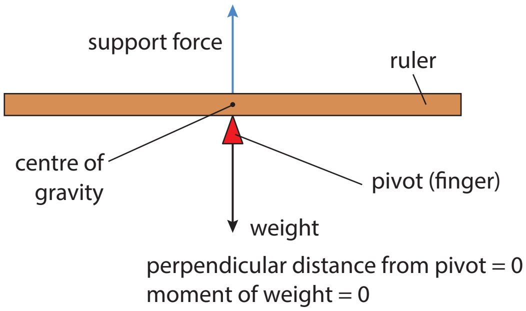


Figure 4.30 Forces acting on the metre rule

The centre of gravity of the metre rule is at the 50 cm mark. Thus, you can balance the rule on your finger tip at the 50 cm mark.

How to locate the centre of gravity of an object

For an object of regular shape and uniform density, the centre of gravity is at its geometrical centre. Examples of regular shapes are rectangles, triangles, circles, cuboids, spheres and rings. The centre of gravity of an object may also lie outside the object. A ring is an example of such an object (Figure 4.31).

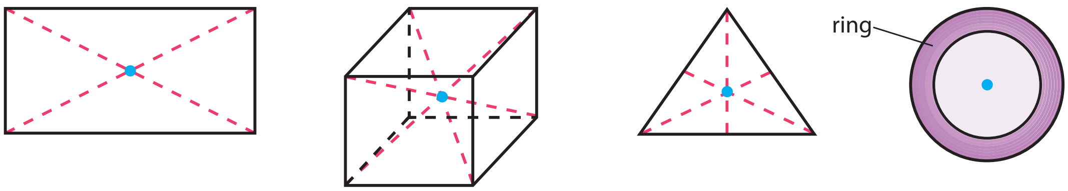


Figure 4.31 The blue dots represent the centre of gravity of regularly-shaped objects

To locate the centre of gravity of an irregularly-shaped plane lamina, we can use a plumb line.

To make a plumb line, attach a weight (e.g. a pendulum bob) to one end of a long string. Then hang the plumb line from a pin and let it move freely about the pin. When the plumb line is perfectly still, *F* and *W* balance each other out such that the resultant force and the resultant moment are both zero (Figure 4.32). The string is on the same straight line that passes through the centre of gravity of the weight.

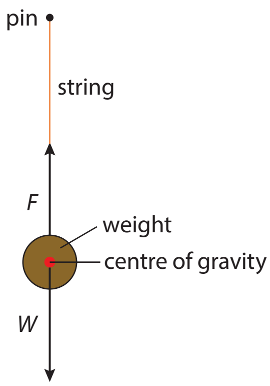


Figure 4.32 Forces acting on a plumb line

ENRICHMENT THINK

Other than a ring, can you think of one other object where the centre of gravity lies outside the object?

WORD ALERT

Lamina: a piece of a material that is thin and flat

QUICK CHECK

The centre of gravity of an object can lie outside the object.

True or false?

Let's Investigate 4C

Objective
To locate the centre of gravity of an irregularly-shaped plane lamina using a plumb line

Materials
irregularly-shaped lamina, plumb line with a pendulum bob, retort stand, split cork, pin

Procedure

1. Make three small holes near the edge of the lamina. The holes should be as far apart as possible from one another. The holes must be small so that not too much of the lamina is removed. An example is given for reference (Figure 4.33).

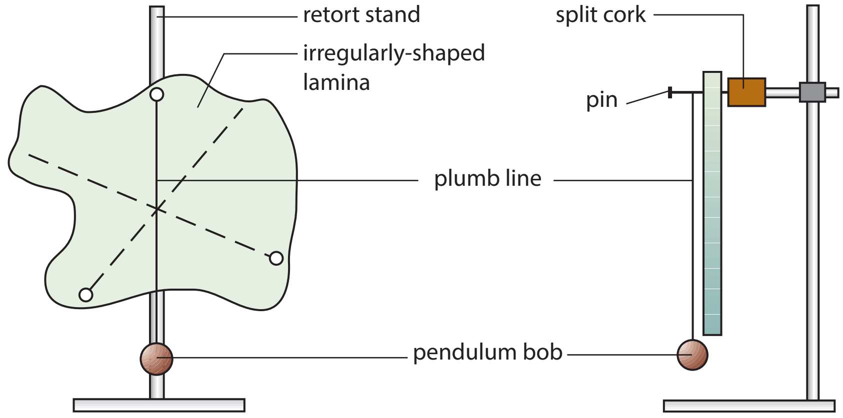


Figure 4.33

2. Hang the lamina freely from a pin on one of the holes.
3. Hang a plumb line from the pin in front of the lamina.
4. When the plumb line is steady, draw dotted lines on the lamina to trace the plumb line.
5. Repeat steps 2 to 4 for the other two holes.

Conclusion
The point of intersection of the three lines is the position of the centre of gravity.

LINK PWB

Practical 4C, pp. XX–XX

Worked Example 4H

A student wants to measure the weight of a uniform metre rule. She hangs a weight of 2.5 N at the 80 cm mark. Then she adjusts the position of the ruler on a pivot until it balances perfectly as shown in Figure 4.34. What is the weight of the ruler? (Note: The centre of gravity of a uniform metre rule is at the 50 cm mark.)

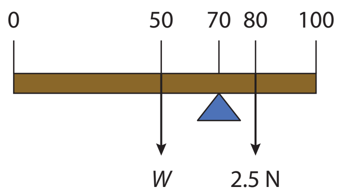


Figure 4.34

Solution
Perpendicular distance from pivot for 2.5 N force
$= 80 - 70 = 10$ cm

Clockwise moment of 2.5 N force $= 2.5 \times 10 = 25$ N cm

Perpendicular distance from pivot for the weight of ruler $= 70 - 50 = 20$ cm

Anticlockwise moment of $W = W \times 20 = 20W$ N cm

Using the principle of moments, $20W = 25$

$$W = \frac{25}{20} = 1.25 \text{ N}$$

How does the centre of gravity affect the stability of an object?

Consider a book with six faces — two broad and four narrow. Suppose we make it stand upright on one of its narrow faces (Figure 4.35(a)). If we give it a slight push, the book will topple (Figure 4.35(b)). The book is unstable.

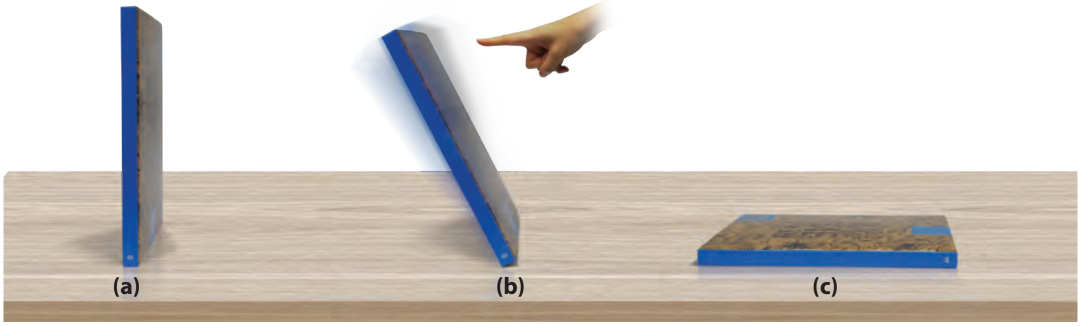
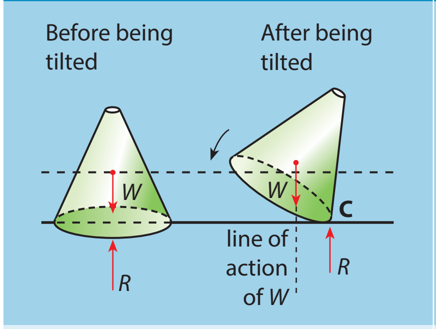


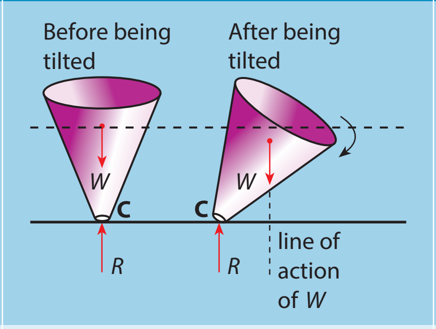
Figure 4.35 *A book standing on one of its narrow surfaces is unstable, but the same book lying flat on its broad surface is stable.*

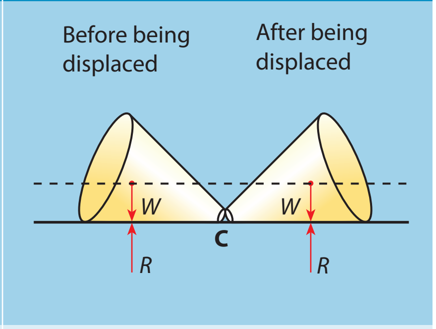
However, if we lay the book flat on one of the broad faces and give it a slight push, the book will not topple (Figure 4.35(c)). It is stable.

The weight of an object acting through its centre of gravity causes it to topple when the resultant moment is not zero. Table 4.7 shows how we can try to balance a paper cone in three ways. The two forces acting on the cone are its weight *W* and the contact force *R*. Notice that the paper cone topples more easily in certain situations.

Table 4.7 *Types of equilibrium*







Stable equilibrium	Unstable equilibrium	Neutral equilibrium
If the cone is slightly tilted, • its centre of gravity rises before returning to its original height; • the line of action through its weight *W* still lies within its base; • the moment of its weight about the contact point **C** causes the cone to return to its original position.	If the cone is slightly tilted, • its centre of gravity drops; • the line of action through its weight *W* lies outside its base; • the moment of its weight about the contact point **C** causes the cone to topple.	If the cone is slightly **displaced**, • its centre of gravity remains at the same height; • the lines of action through its weight *W* and contact force *R* coincide; • the moment of its weight about the contact point **C** is zero; it stays in the position to which it is displaced.

From Table 4.7, we can conclude that the stability of an object depends on the location of its centre of gravity and the width of its base.

WORD ALERT

Displaced: shifted, moved from its original place

To increase the stability of an object,
- its centre of gravity should be kept as low as possible (i.e. more mass packed at its bottom);
- its base area should be kept as wide as possible.

Many objects in our daily lives are designed to increase their stability. Racing cars, Bunsen burners, table lamps and standing fans have large and heavy bases to lower their centre of gravity. Look around you. What other examples can you give?

Worked Example 4I

Figure 4.36 shows the rest position and the displaced position of a balancing toy. Its centre of gravity is indicated by the letter G. Explain briefly why the toy eventually returns to its rest position after being released from its displaced position.

(a) Rest position **(b)** Displaced position

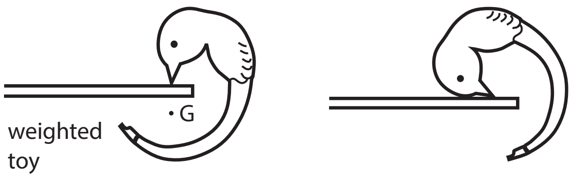


Figure 4.36

Solution

The centre of gravity is the point through which the weight of an object acts. When the toy is at rest, its centre of gravity G is directly below the pivot (i.e. its beak).

When the toy is displaced, G is moved upwards and to the right (Figure 4.37). Its weight now has a turning effect about the pivot. The moment of the weight about the pivot causes the toy to rotate clockwise towards its rest position.

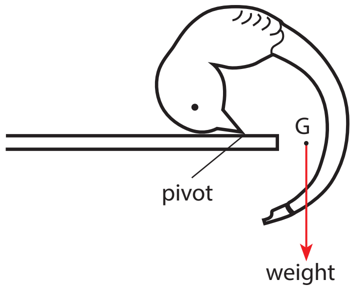


Figure 4.37

Let's Practise 4.4

1 **(a)** What is the centre of gravity of an object?
  (b) Is the centre of gravity of an object the same whether it is near the surface of the Earth or the Moon? Explain.

2 **(a)** How does the position of the centre of gravity affect the stability of an object?
  (b) A minibus is travelling on the road carrying heavy loads on its roof rack. There are no passengers inside the minibus. When turning a corner, the driver drives very slowly. Explain why.

3 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

ENRICHMENT *INFO*

Defying Gravity

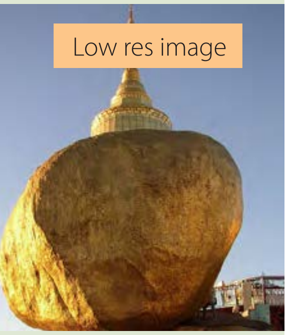


Figure 4.38 *Kyaiktoyo pagoda or Golden Rock*

The Kyaiktoyo pagoda in Myanmar is a sacred site for Buddhists. It sits on top of a huge heavy rock resting at the edge of a cliff. Many worshippers meditate underneath the rock, perhaps hoping to be in a state of equilibrium just like the rock. How does this rock stay put? The answer could be its centre of gravity.

ENRICHMENT *ACTIVITY*

Make your own balancing toy using suitable materials such as sticks, modelling clay, paper clips, cork, cardboard, etc.

What principles have you used in order to make your toy balance?

Compare your toy with those of your classmates.

LINK TWB

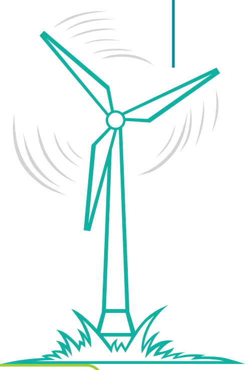
Exercises 4D–4E, pp. XX–XX

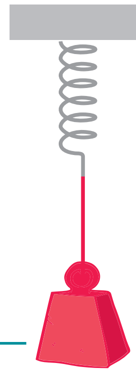
Exercise 4F Let's Reflect, p. XX

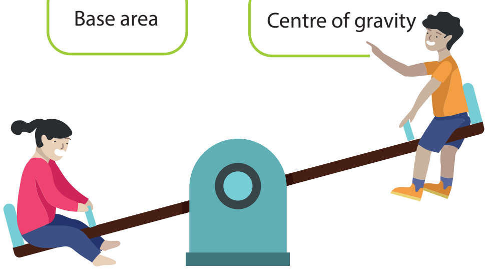
Let's Map It

FORCES F (SI unit: N)

- **cause** → Objects to change in size and/or shape
  - **such as** → A spring
    - **whose spring constant k is a ratio given by** → Ⓢ $k = \frac{F}{x}$ where F = load, x = extension
      - **represented using** → Ⓢ Load-extension graph within the limit of proportionality
- **affect** → Motion
  - **described by** → Ⓢ Resultant force F (N) = mass (kg) × accelleration (m/s)
    - **applies to**
      - Balanced forces (Resultant F = 0 N)
        - **for an object**
          - At rest
          - Moving at a constant velocity
      - Unbalanced forces (Resultant $F \neq$ 0 N)
        - **for an object**
          - Ⓢ Moving in a circle
          - Accelerating due to a push or pull
          - Decelerating due to friction or drag
- **produce** → Turning effect known as moment of a force (SI unit: N m)
  - **defined as** → Moment (N m) = force (N) × perpendicular distance of the force from the pivot
    - **can be**
      - Anticlockwise
      - Clockwise
        - **for an object in equilibrium** → Principle of moments: Sum of clockwise moments = sum of anticlockwise moments
          - **which relate to** → Stability of an object
            - **affected by its**
              - Base area
              - Centre of gravity







Let's Review

Section A: Multiple-choice Questions

1 What quantities of an object can a force change?
- **A** Mass and length
- **B** Speed and length
- **C** Speed and weight
- **D** Weight and mass

2 A feather is floating downwards at constant speed. What is the resultant force on the feather?
- **A** Air resistance
- **B** Gravitational force
- **C** Pointing downwards
- **D** Zero

3 S A resultant force of 4 N causes an object to accelerate at 2 m/s^2. What force is needed to make the same object accelerate at 3 m/s^2?
- **A** 2 N
- **B** 4 N
- **C** 6 N
- **D** 8 N

4 S Figure 4.38 shows a car moving in a circular path. In which direction is the resultant force acting on the car?

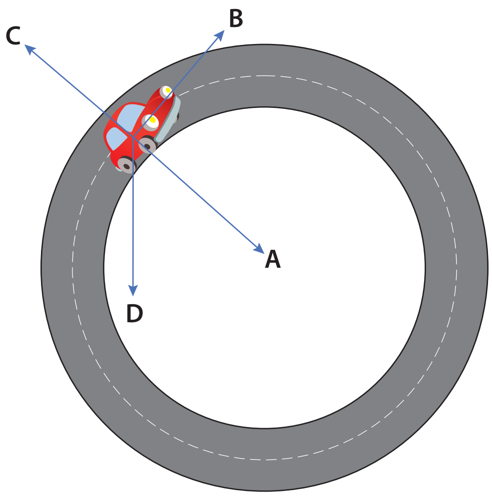


Figure 4.38

5 Which of the following is the SI unit for moment of a force?
- **A** kg
- **B** kg m
- **C** N
- **D** N m

6 Which statement describes an object in equilibrium?
- **A** The resultant force is zero.
- **B** The resultant moment is zero.
- **C** The resultant force and resultant moment are zero.
- **D** There is no force acting on the object.

7 A boy is planning to design a water bottle. Which procedure should he follow to design the most stable water bottle?
- **A** Make the centre of gravity high and the base area large.
- **B** Make the centre of gravity high and the base area small.
- **C** Make the centre of gravity low and the base area large.
- **D** Make the centre of gravity low and the base area small.

Section B: Short-answer and Structured Questions

1 Figure 4.39 shows the forces acting on a toy boat.

Figure 4.39

(a) Calculate the resultant force on the boat.
(b) Some time later, the boat moves at constant speed. What is the resistive forces acting on the boat?

2 **(a)** What is the unit of the moment of a force?
(b) A girl and her brother are sitting on a see-saw. The girl weighs 500 N. Her brother weighs 700 N. Figure 4.40 shows their positions on the see-saw.

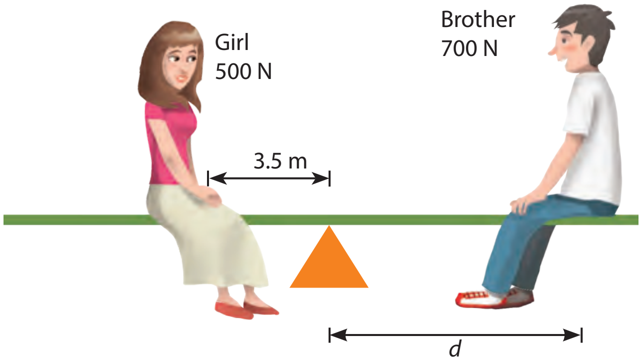


Figure 4.40

Let's Review

(i) The see-saw is in equilibrium. State how the see-saw can be in equilibrium.

(ii) Calculate how far from the pivot should the brother should be sitting.

3 Figure 4.41 shows a load of 3000 N balanced by a concrete block of weight W, on the arm of a crane. The concrete block can be moved along the arm.

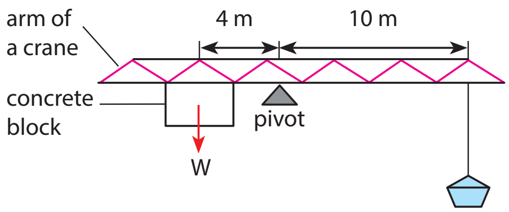


Figure 4.41

(a) What is the moment of the load?

(b) Using the principle of moments, calculate the weight W of the concrete block.

(c) The load is replaced by a new load weighing 1800 N. What is the new distance of W from the pivot when the arm is balanced?

4 Ⓢ Figure 4.42 shows a uniform 1 m plank XY weighing 200 N hinged to a wall at X. A 500 N force acts downwards on the plank 20 cm from X. The plank is held horizontally by a force F acting upwards from Y. Using X as pivot, calculate the magnitude of force F.

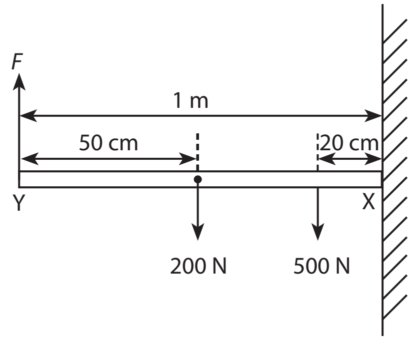


Figure 4.42

S CHAPTER

5 Momentum

PHYSICS WATCH

Scan this page to watch a clip on the impact of a collision.

Trains are an important means of transport in many parts of the world. In India alone, more than 20 million people board trains to move from one place to another every day. However, we hear of train accidents happening now and then. When fast-moving trains or trains carrying heavy loads collide, it poses a great danger to human lives and causes great damage. Engineers have been conducting case studies to find ways to increase safety for passengers and reduce damage. In some studies, trains were purposely crashed into concrete walls — without passengers, of course! This was done to investigate the impact upon collision.

QUESTIONS

- Name two physical quantities of the train that will affect the impact of a collision.
- State how each of the two physical quantities affects the impact of a collision.

5.1 What Is Momentum?

In this section, you will learn the following:
- Define momentum as mass × velocity.
- Recall and use the equation $p = mv$.

An object has momentum when it is in motion.

A fast-moving object has more momentum than a slower-moving object of the same mass (Figure 5.1).

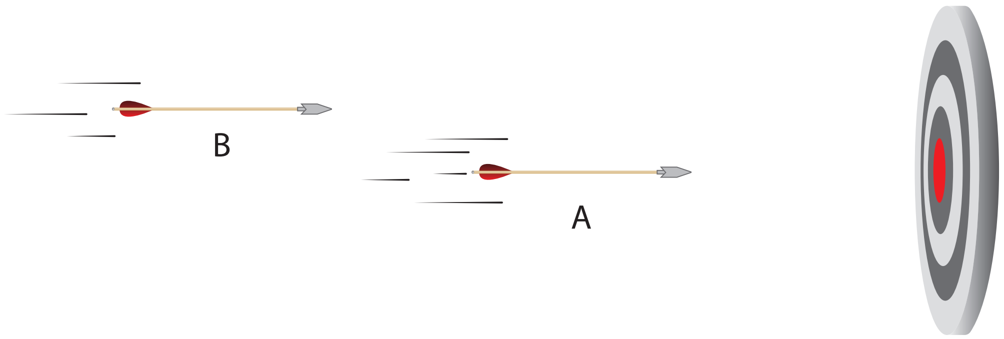


Figure 5.1 *Two identical arrows move towards a target at different speeds. Which of the two arrows has more momentum?*

A massive moving object has more momentum than a lighter moving object of the same velocity (Figure 5.2).

Figure 5.2 *An elephant and a dog are moving at the same velocity to chase the hunter. Which animal has more momentum?*

Mass and velocity are two physical quantities that determine the momentum of an object.

Momentum is defined as the product of mass and velocity.

Its SI unit is **kilogram metre per second (kg m/s)**.

Momentum = mass × velocity

$\boldsymbol{p = mv}$ where p = momentum m
m = mass v
v = velocity

Momentum is a vector quantity. It has both magnitude and direction.

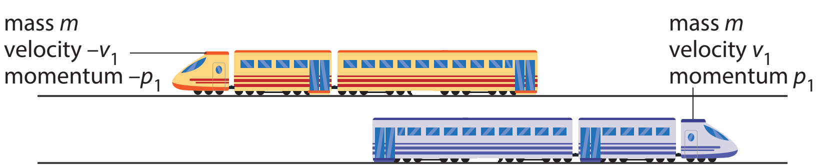


Figure 5.3 *The trains have different momentums as the trains are travelling in different directions.*

LINK

Is mass a vector or a scalar quantity? What about velocity?

Recall what you have learnt in Chapter 1.

QUICK CHECK

The momentum of an object can have a negative value.

True or false?

HELPFUL NOTES

To calculate momentum in its SI unit (kg m/s), the unit for mass (*m*) should be kilogram (kg) and the unit for velocity (*v*) should be metre per second (m/s).

Worked Example 5A

Calculate is the momentum of

(a) a runner of mass 50 kg running at 4 m/s;

(b) a man of mass 70 kg walking at 1.2 m/s;

(c) a soccer ball of mass 400 g (0.4 kg) moving at 25 m/s;

(d) a car of total mass 1000 kg travelling at 18 km/h (5 m/s).

Solution

By definition, momentum = mass × velocity

(a) momentum of the runner = 50 kg × 4 m/s = 200 kg m/s

(b) momentum of the man = 70 kg × 1.2 m/s = 84 kg m/s

(c) momentum of the soccer ball = 0.4 kg × 25 m/s = 10 kg m/s

(d) momentum of the car = 1000 kg × 5 m/s = 5000 kg m/s

Worked Example 5B

(a) What is the speed of a bus with mass 8000 kg and momentum of 88 000 kg m/s?

(b) A car travelling at 12 m/s has a momentum of 14 400 kg m/s. Calculate its mass.

Solution

(a) Given: Mass $m = 8000$ kg

Momentum $p = 88\,000$ kg m/s

By definition, $p = mv$

$$v = \frac{p}{m} = \frac{88\,000 \text{ kg m/s}}{8\,000 \text{ kg}} = 11 \text{ m/s}$$

(b) Given: Momentum, $p = 14\,400$ kg m/s

Velocity, $v = 12$ m/s

By definition, $p = mv$

$$m = \frac{p}{v} = \frac{14\,400 \text{ kg m/s}}{12 \text{ m/s}} = 1200 \text{ kg}$$

Let's Practise 5.1

1 Fill in the correct physical quantities in the word equation:

momentum = ________________ × ________________

2 What is the SI unit of momentum?

3 Is momentum a scalar or a vector quantity?

4 Calculate the momentum of a ball of mass 0.4 kg moving at 12 m/s.

5 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

Exercise 5A, pp. XX–XX

5.2 Momentum, Impulse and Force

In this section, you will learn the following:

- Define impulse as force × time for which force acts.
- Recall and use the equation $F\Delta t = \Delta(mv)$.
- Define resultant force as the change in momentum per unit time.
- Recall and use the equation $F = \frac{\Delta p}{\Delta t}$.

How is impulse related to change in momentum?

Mass and velocity are physical quantities associated with momentum. Besides these two quantities, what other physical quantities do you associate with momentum? Do you think of force and time? Figure 5.4 shows a book being pushed across a table with force F for a period of time Δt.

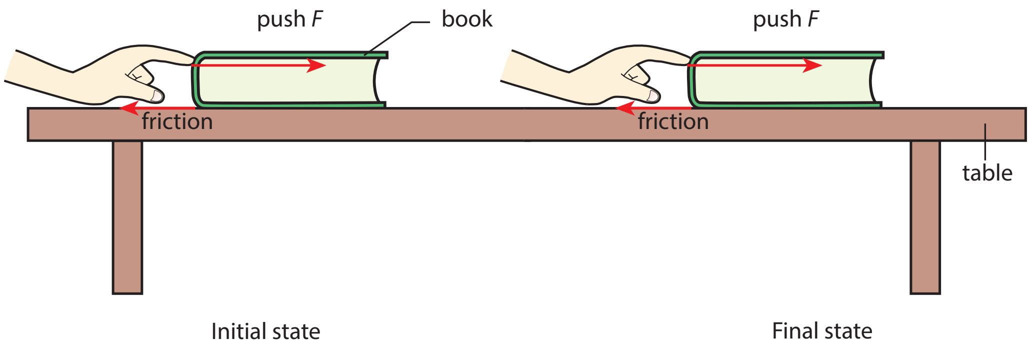


Figure 5.4 *Pushing a book across a table top*

During this period of time Δt when force F acts, the velocity of the book changes. Therefore, its momentum changes. We can write the change in momentum
as $\Delta(mv)$.

The change in momentum can be shown to be equal to the product of the force and the period of time for which the force acts.

$F\Delta t = \Delta(mv)$ or $F\Delta t = \Delta p$

Impulse is the product of force and the period of time for which force acts.

Its SI unit is **newton second (N s)**.

Impulse = force × time = $F\Delta t$

The force applied to an object may not be constant throughout the motion of the object. The force F in the equation in such a situation is the average resultant force acting for a period of time Δt.

Figure 5.5 *The force on the ball by the batter may not be constant from the moment the bat touches the ball to the moment the ball leaves the bat.*

HELPFUL NOTES

Force is a derived quantity, where $F = ma$. The unit of force (newton, N) can be written as kg m/s^2.

Thus, the unit of $F\Delta t$ = kg m/s^2 x s = kg m/s.

The SI unit for impulse (N s) is equivalent to the SI unit for momentum (kg m/s).

WORD ALERT

Constant: stay the same

HELPFUL NOTES

Momentum and impulse are useful concepts for analysing collisions or interactions between two objects.

Worked Example 5C

Figure 5.6 shows a boy kicking a stationary ball of mass 0.4 kg with an average force of 100 N. The ball moved at 5 m/s immediately afterwards. Calculate

(a) the impulse of the force exerted on the ball;

(b) the time of contact between his boot and the ball.

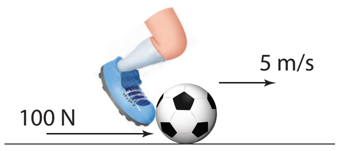


Figure 5.6

Solution

Given: $F = 100$ N, $m = 0.4$ kg, $v_1 = 0$ m/s, $v_2 = 10$ m/s

(a) Impulse = change in momentum = $\Delta(mv)$

$= (0.4 \text{ kg} \times 5 \text{ m/s}) - (0.4 \text{ kg} \times 0 \text{ m/s})$

$= 2$ kg m/s $= 2$ N s

(b) Using $F\Delta t = \Delta(mv)$, $\Delta t = \dfrac{\Delta(mv)}{F} = \dfrac{2 \text{ N s}}{100 \text{ N}} = 0.02$ s

The time of contact between his boot and the ball is 0.02 s.

HELPFUL NOTES

$F = \dfrac{\Delta p}{\Delta t}$ is the same as $F = ma$ for special cases when the mass of the object does not change.

How is resultant force related to change in momentum?

We have learnt that the impulse of a resultant force equals the change in momentum of the object, i.e., $F\Delta t = \Delta p$.

Change in momentum, $\Delta p = F\Delta t$

$$\therefore \boldsymbol{F} = \frac{\boldsymbol{\Delta p}}{\boldsymbol{\Delta t}}$$

Resultant force *F* on an object is the change in momentum per unit time.

The three quantities momentum, impulse and resultant force are all related as shown in Table 5.1.

Table 5.1 *A summary of momentum, impulse and resultant force*

Physical quantity	Symbol	Defining equation	SI unit
Momentum	p	$p = mv$	kg m/s
Impulse	–	Impulse $= F\Delta t$	N s
Resultant force	F	$F = \dfrac{\Delta p}{\Delta t}$	N

The quantities momentum, impulse and force are vector quantities. When these quantities are used in calculations, their directions are indicated as '+' and '–' signs. To perform calculations with vector quantities, assign one direction as positive. The opposite direction is then negative and you can add them like you do for finding forces along the same straight line.

ENRICHMENT INFO

Symbol for Momentum

Have you wondered why the symbol used for momentum is p?

The symbol p is likely to be derived from the Latin word *petere*, which means "to go". The symbol m is not used even though momentum starts with the letter "m" as the same symbol was already in use for mass.

Worked Example 5D

Suppose a car of mass 1250 kg crashes into a concrete wall. The speed of the car is 7.2 m/s just before it hits the wall. Calculate the average force on the car as it hits the wall if it takes

(a) 0.1 s for the car to come to a complete stop;

(b) 0.4 s for the car to come to a complete stop.

Solution

The momentum of the car just before the crash = mass × velocity = 1250 × 7.2 = 90 000 kg m/s in the forward direction

After the crash, the car stops moving. The momentum of the car after the crash = 0 kg m/s.

Change in momentum of the car, $\Delta p = 0 - 90\,000 = -90\,000$ kg m/s

$= -90\,000$ N s

(a) Average force acting on the car, $F = \dfrac{\Delta p}{\Delta t} = \dfrac{-90\,000 \text{ N s}}{0.1 \text{ N}} = -900\,000$ N

The negative sign means the force is in the backward direction.

(b) Average force acting on the car, $F = \dfrac{-90\,000 \text{ N s}}{0.4 \text{ N}} = -225\,000$ N

Worked Example 5D (b) shows that the force is much smaller with a longer stopping time. In order to increase the stopping time during a crash, a car is designed with a 'crumple zone'. This allows the front of the car to collapse when a collision occurs. The car can then come to a stop with a slightly longer time (Figure 5.7).

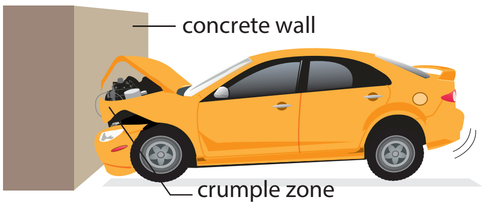


Figure 5.7 *The crumple zone is a safety feature to reduce the force on the car.*

Safety features, such as seat belts and safety helmets, reduce the force by increasing the time taken for the momentum to change to zero. This helps to reduce the disastrous impact of collisions.

Worked Example 5E

A ball of mass 0.625 kg hits the ground at 4 m/s. It bounces back from the ground at 3.8 m/s. Calculate the impulse on the ball.

Solution

Take moving away from the ground (i.e. upwards) as the positive direction.

Given: $m = 0.625$ kg, $u = -4.0$ m/s, $v = 3.8$ m/s

Impulse = change in momentum = Δp

$= (0.625 \text{ kg} \times 3.8 \text{ m/s}) - (0.625 \text{ kg} \times -4.0 \text{ m/s})$

$= 4.88$ kg m/s $= 4.88$ N s

The ground pushes up on the ball with an impulse of 4.88 N s.

ENRICHMENT THINK

Suppose you board a bus. All the seats are taken. You and a few others have to stand. The bus picks up speed and continues its journey. Suddenly, all the standing passengers are jolted out of position when the bus reaches the traffic light.

1 Why do you think that happens?

2 What would you expect the bus driver to do to give passengers a more comfortable ride?

PHYSICS WATCH

Scan this page to watch a clip on the effect of the crumple zone of a car.

QUICK CHECK

Impulse on an object can be reduced by decreasing stopping time.

True or false?

Let's Practise 5.2

1 Fill in the correct physical quantity in the word equation:
Impulse = ________ × ________
2 What is the SI unit for impulse?
3 Is impulse a scalar or a vector quantity?
4 The resultant force is the change in ________________________ per unit _______________.
5 A boy kicks a ball, which is resting on the ground. The boy's boot is in contact with the ball for 0.040 s. The average force on the ball is 150 N. Calculate the impulse of the boot on the ball.
6 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

Exercise 5B, pp. XX–XX

5.3 The Principle of Conservation of Momentum

In this section, you will learn the following:

- Apply the principle of the conservation of momentum to solve simple problems.

What happens to the momentum of moving objects when they collide?

When two moving objects collide, the total momentum of the two objects just before the collision is the same as the total momentum of the objects immediately after the collision. This is also known as the **principle of conservation of momentum**.

PHYSICS WATCH

Scan this page to watch a clip on how the Newton's cradle works.

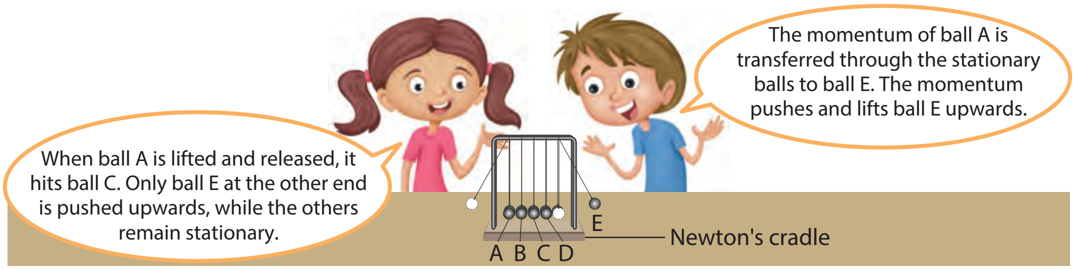


Figure 5.8 Newton's cradle is a device used to show the principle of conservation of momentum.

Worked Example 5F

Trolley A of mass 2 kg travelling at 2 m/s collided with a stationary trolley B of mass 3 kg. The two trolleys stuck together after the collision. Figure 5.9 shows what happened before and after the collision.

(a) Calculate

(i) the velocity of the two combined trolleys immediately after they collided;

(ii) the impulse experienced by trolley B;

(iii) the change in momentum experienced by trolley A.

(b) Comparing your answers to (ii) and (iii), what do you observe?

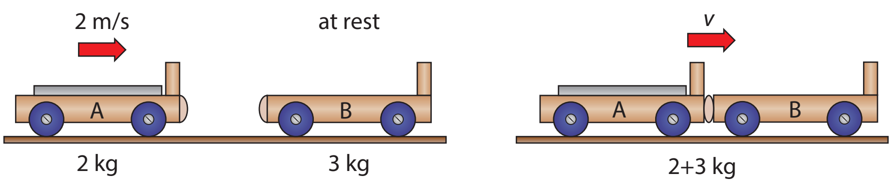


Figure 5.9 *Collision of two trolleys in a straight line*

Solution

(a) Given: Mass of trolley A, $m_1 = 2$ kg, mass of trolley B, $m_2 = 3$ kg

velocity of trolley A, $v_1 = 2$ m/s, velocity of trolley B, $v_2 = 0$ m/s

Total momentum before collision $= m_1v_1 + m_2v_2 = 2 \text{ kg} \times 2 \text{ m/s} + 3 \text{ kg} \times 0 \text{ m/s}$

$= 4$ kg m/s

Total momentum after collision $= (m_1 + m_2)v = (2 + 3) \text{ kg} \times v \text{ m/s} = 5v$ kg m/s

Applying the principle of conservation of momentum,

Total momentum after collision = total momentum before collision

$$5v = 4$$

$$v = \frac{4}{5} = 0.8 \text{ m/s}$$

The speed of the combined trolleys was 0.8 m/s.

(b) After the collision, momentum of trolley B $= 3 \text{ kg} \times 0.8 \text{ m/s} = 2.4$ kg m/s

Impulse = change in momentum = 2.4 N s − 0 N s

= 2.4 N s in the forward direction

The impulse experienced by trolley B is 2.4 N s in the forward direction.

(c) Before the collision, momentum of trolley A $= 2 \text{ kg} \times 2 \text{ m/s} = 4$ kg m/s

After the collision, momentum of trolley A $= 2 \text{ kg} \times 0.8 \text{ m/s} = 1.6$ kg m/s

Change in momentum = 1.6 kg m/s − 4 kg m/s = −2.4 kg m/s

(d) Impulse experienced by trolley A = change in momentum of trolley A = −2.4 N s

Therefore, trolley A experienced a backward impulse of 2.4 N s, while trolley B experienced a forward impulse of 2.4 N s.

ENRICHMENT *ACTIVITY*

1 Take two identical balls of the same mass and size. Place one ball at rest. Launch one ball at a speed such that it collides with the other ball.

2 Take two balls of different masses and sizes. Place the heavier ball at rest. Launch the lighter ball at a speed such that it collides with the heavier ball.

Describe what happens in each case. Share your findings with the class.

QUICK CHECK

The total momentum of a system is always conserved.

True or false?

Worked Example 5G

Ball A of mass 0.12 kg is moving forward at a speed of 0.40 m/s in a straight line on a smooth surface. It collides with a stationary ball B of mass 0.09 kg. Ball B moves forward at a velocity of 0.40 m/s. Figure 5.10 shows the balls before and after the collision. What is the velocity of ball A after the collision?

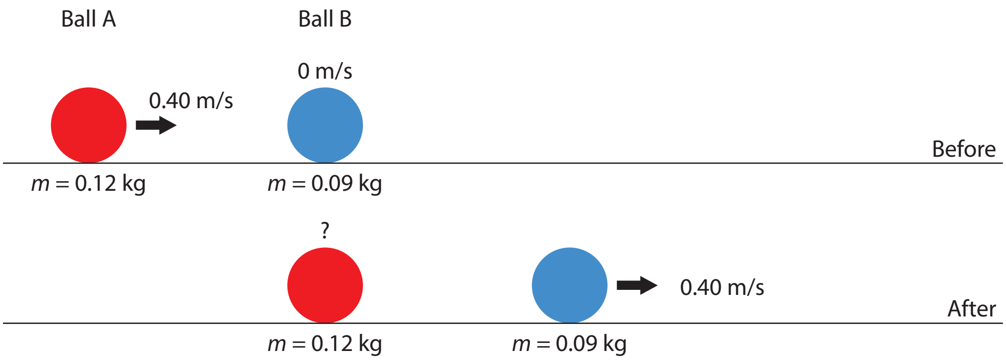


Figure 5.10

Solution

Let the speed of ball A after the collision be v m/s.

Total momentum before collision = 0.12 kg × 0.40 m/s + 0.09 kg × 0 m/s

= 0.048 kg m/s in the forward direction

Total momentum after collision = 0.12 kg × v m/s + 0.09 kg × 0.40 m/s

= (0.12v + 0.036) kg m/s in the forward direction

Applying the principle of conservation of momentum,

Total momentum after collision = total momentum before collision

$$(0.12v + 0.036)\text{ kg m/s} = 0.048\text{ kg m/s}$$

$$v = \frac{(0.048 - 0.036)\text{ kg m/s}}{0.12\text{ kg}} = 0.10\text{ m/s}$$

LINK PWB

Practical 5, pp. XX–XX

Let's Practise 5.3

1 What is the principle of conservation of momentum?

2 A car of mass 1200 kg is travelling at 8.0 m/s. It collides with a lorry of mass 2800 kg travelling at 2 m/s in the same direction. After the collision, the two vehicles stick together. Calculate their speed immediately after the collision.

3 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

Exercises 5C–5D, pp. XX–XX

Exercise 5F Let's Reflect, p. XX

Let's Map It

MOMENTUM p

SI unit: kg m/s

Vector quantity

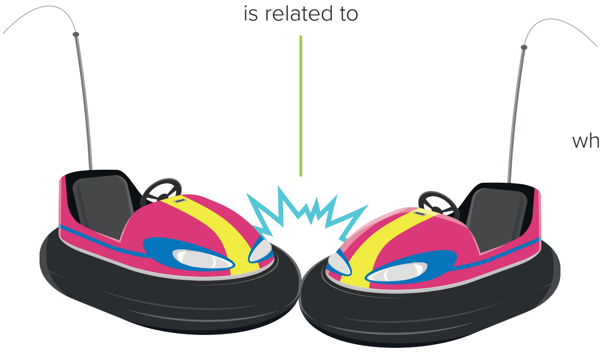
is defined as

The product of mass and velocity

$p = mv$

where
p = momentum
m = mass
v = velocity

is related to



Impulse

where

Impulse = change in momentum
$F\Delta t = \Delta p$

Force

where

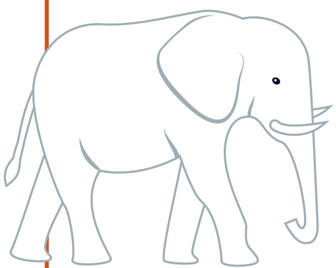
Resultant force $F = \frac{\Delta p}{\Delta t}$

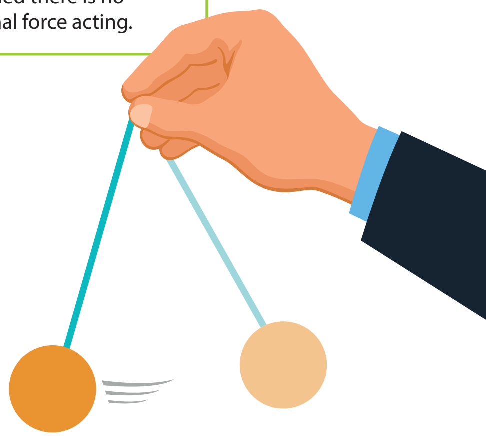
is conserved in collisions between objects governed by

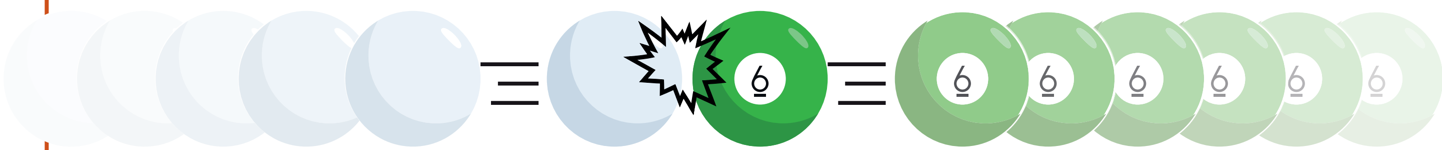
The principle of conservation of momentum

which states that

When objects collide, the total momentum of the objects before a collision is the same as the total momentum of the objects after the collision, provided there is no external force acting.







Let's Review

Section A: Multiple-choice Questions

1 Which statement defines momentum?

A Momentum = mass × velocity

B Momentum = mass × velocity × velocity

C Momentum = $\frac{\text{mass}}{\text{velocity}}$

D Momentum = $\frac{\text{velocity}}{\text{mass}}$

2 A truck of mass 10 000 kg is moving at 5.0 m/s. Calculate the momentum of the truck.

A 5.0×10^{-4} kg m/s

B 2.0×10^{3} kg m/s

C 5.0×10^{4} kg m/s

D 2.5×10^{5} kg m/s

3 Which statement defines impulse?

A Impulse = mass × velocity

B Impulse = mass × acceleration

C Impulse = force × distance

D Impulse = force × time for which force acts

4 A bullet of mass 0.05 kg was fired into a wooden block of mass 1.95 kg resting on a frictionless horizontal surface. Upon collision, the bullet and the block were stuck together. Immediately after the collision, the bullet and the block moved at a constant velocity of 15 m/s. With what speed did the bullet hit the block?

A 15 m/s

B 30 m/s

C 585 m/s

D 600 m/s

5 A basketball player is bouncing a ball on the ground. The ball hits the ground 10 times in 20 seconds. The average change in momentum for each collision is 15 kg m/s. What is the force that the ground exerts on the ball?

A 0.75 N

B 2 N

C 7.5 N

D 20 N

Section B: Short-answer and Structured Questions

1 **(a)** Complete the word equation:

momentum = __________ × __________

(b) Figure 5.11 shows an empty freight car moving at 8 m/s towards a stationary loaded car as shown. It collides with the loaded car and the cars stick together after the collision.

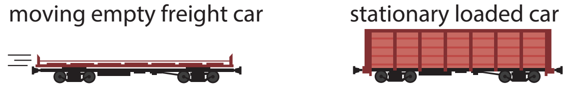


Figure 5.11

The mass of the empty freight car is 2000 kg.

(i) Calculate the momentum of the empty freight car before the collision.

(ii) The mass of the loaded car is 8000 kg. With what speed do the combined cars start to move?

2 A resultant force of 16 N acts for 5 s on an object. The mass of the object is 2 kg. Calculate

(a) the change in momentum of the object;

(b) the impulse of the force;

(c) the change in speed of the object.

3 Two ice skaters A and B are stationary on a skating rink. The mass of skater A is 80 kg. The mass of skater B is 50 kg. They face each other and push each other off. Skater A moves off in a straight line with velocity of 0.5 m/s. Calculate

(a) the momentum of skater A;

(b) the momentum of skater B;

(c) the velocity of skater B.

CHAPTER 6

Energy, Work and Power

PHYSICS WATCH

Scan this page to watch a clip of a roller coaster ride.

What energy conversions take place?

QUESTIONS

- Why is a powerful motor needed to launch the roller coaster cars to their starting positions?
- How do you think the speeds of the roller coaster cars will vary as they move along the high points and low points of the tracks?
- If you were to ride the roller coaster, at which point would you feel the greatest thrill? Why do you think so?

Standing at 42.5 metres, the *Battlestar Galactica* at the Universal Studios, Singapore, is the tallest duelling roller coaster in the world. It's *Human* versus *Cyclon*. By means of a powerful motor, these two roller coaster cars are launched towards their high starting positions at high speeds. Once ready, they will move along tracks designed to produce near misses. Are you game for some adventure? Let the duel begin.

6.1 Energy

In this section, you will learn the following:

- State that energy may be stored in different forms.
- Describe how energy is transferred between stores during events and processes.
- S Recall and use the expressions *kinetic energy* = $\frac{1}{2}mv^2$ and *change in gravitational potential energy* = $mg\Delta h$.
- Know and apply the principle of conservation of energy to simple examples using flow diagrams.
- S Apply the principle of conservation of energy to complex examples involving multiple stages including the interpretation of Sankey diagrams.

WORD ALERT

Capacity: ability

LINK

You will learn more about work done in Section 6.2 of this chapter.

What is energy?

What does the term *energy* bring to mind? Someone exercising vigorously? Tidal waves crashing against the shore? You would probably relate energy with strong forces that produce motion. In physics:

Energy is the capacity to do work. The SI unit of energy is the **joule (J)**.

Work usually means making a body or an object move to achieve a purpose. For example, when a person rows a boat, work is done. In order to do work, energy is transferred between objects or converted from one form to another. Figure 6.1 shows the different forms of energy.

Different Forms of Energy

Potential energy

Potential energy is the stored energy in a system. This form of energy is due to the state, shape or position of the system. There are different types of potential energy. Each of these types of potential energy can be converted into other forms of energy.

Kinetic energy

Kinetic energy is the energy of a body due to its motion. Thus, wind has kinetic energy and so do sea waves, a spinning frisbee and a rolling soccer ball.

Kinetic energy can be used to do work. For example, wind and sea waves can be used to turn turbines, which convert kinetic energy to electrical energy.

Chemical potential energy

Chemical potential energy is the energy stored in a substance due to the *position of the atoms or electrons* in the substance. The food that we eat, fossil fuels and batteries contain chemical potential energy.

Elastic (strain) energy

Elastic (strain) energy is the energy stored in a body due to its *elastic deformation*. A spring or rubber band possesses elastic potential energy when it is compressed or stretched. This energy can be converted to kinetic energy when the spring or rubber band is released.

Gravitational potential energy

Gravitational potential energy is the energy stored in a body due to its height from the ground. An object has gravitational potential energy when it is raised to a height above the ground. When the object is released, its gravitational potential energy is converted to kinetic energy as it falls.

Electrostatic potential energy

Electrostatic potential energy is the energy stored in the *electric fields of static charges*. A capacitor is a common device that stores electrostatic potential energy in the flash unit of a camera. When the flash is used, the electrostatic potential energy from the capacitor is converted to light energy to brighten up the scene .

Figure 6.1 *The different forms of energy*

Electrical energy

Electrical energy is the energy of an *electric charge due to its motion and position*. It is used extensively in our everyday lives.

Lightning has electrical energy.

Internal (thermal) energy

Internal or thermal energy is the energy stored in a body due to its *temperature*. The particles of a hotter body possess more internal energy than those of a colder body. Internal energy is transferred from the hotter body to the colder body.

A hot metal has a high internal energy.

Electromagnetic, sound and other waves

Light is an *electromagnetic wave* that is visible to the eye. It is made up of electric and magnetic fields oscillating at a certain range of frequency within the electromagnetic spectrum.

Sound is a *mechanical wave* that travels through a medium. It is caused by vibrating particles. We hear sound when the vibrating particles cause our ear drum to vibrate.

LEDs are used to convert electrical energy to light energy to light up the streets.

Nuclear energy

Nuclear energy is the energy *released during a nuclear reaction*. It can be found in the nuclei of atoms of radioactive substances such as uranium.

Nuclear power plants generate electricity from nuclear energy.

LINK

How is electrical energy related to electricity? Find out more in Chapter 16.

ENRICHMENT *INFO*

Solar Wind Power

You have probably heard of solar power and wind power. But what is solar wind power?

Solar wind is a stream of energised charged particles that flow out from the Sun. In theory, it is possible to capture this stream of particles using satellite and transmit it back to Earth.

The potential is huge. It is believed that solar wind power could meet our energy needs more than a hundred billion times compared to solar power or wind power alone.

Figure 6.2 *An aurora, a natural light display, as seen in the Earth's sky near the polar regions is caused by solar wind.*

ENRICHMENT *THINK*

Nuclear energy is useful, but it can be very dangerous. Should we promote the use of nuclear energy? Discuss.

We can use formulae to calculate the amount of energy a body has.

To find out the amount of **kinetic energy**, we use the following equation:

$$E_k = \frac{1}{2}mv^2$$

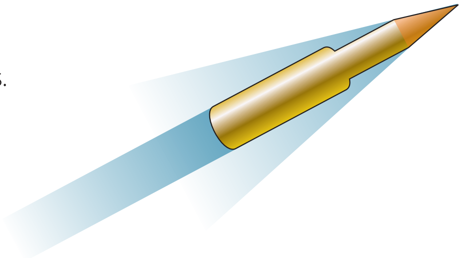
where E_k = kinetic energy (in J)
m = mass of the body (in kg)
v = speed of the body (in m/s)

To find out the amount of **gravitational potential energy**, we use the following equation:

$$\Delta E_p = mg\Delta h$$

where E_p = gravitational potential energy (in J)
m = mass of the body (in kg)
g = gravitational field strength (in N/kg)
h = height (in m)

Worked Example 6A



A bullet of mass 0.02 kg travels at a speed of 1200 m/s. Calculate its kinetic energy.

Solution

Kinetic energy of bullet $= \frac{1}{2}mv^2$

$= \frac{1}{2}(0.02)(1200)^2$

$= 14\,400$ J

Worked Example 6B

A package of 5 kg is lifted vertically through a distance of 10 m at a constant speed (Figure 6.3). Taking the acceleration due to gravity to be 10 m/s², calculate the gravitational potential energy gained by the package.

Solution

Gravitational potential energy of the package $= mgh$

$= (5)(10)(10)$

$= 500$ J

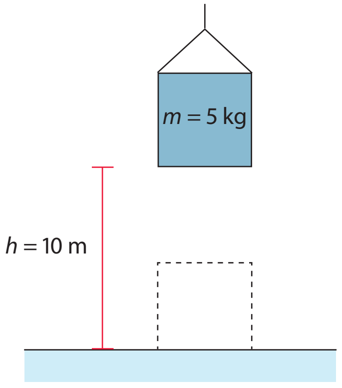


Figure 6.3

What is the principle of conservation of energy?

If you strike a match, you will get a burning flame. The chemical energy found in the substance of the match head is converted to thermal and light energy. When work is done, energy is converted from one form to another. The total amount of energy before and after the conversion is the same as shown in Figure 6.4.

Figure 6.4 *When energy is converted from one form to another, the total amount remains constant.*

The **principle of conservation of energy** states that energy cannot be created or destroyed. It can be converted from one form to another or transferred from one body to another. The total amount of energy remains constant.

Examples of energy conversions

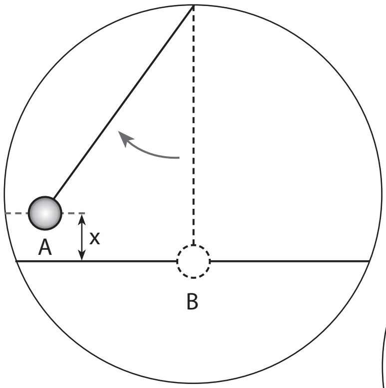
(a) An ideal pendulum swinging

Figure 6.5 illustrates what happens when an ideal pendulum is swinging. The energy conversions taking place is shown by the **flow diagram**. An ideal pendulum will swing forever, with its gravitational potential energy converting to kinetic energy and vice versa. Since the total amount of energy is conserved, energy is not lost from the pendulum, and hence it does not stop swinging.

Figure 6.5 Energy conversion in an ideal pendulum

① The pendulum bob is displaced to position A at height x above the horizontal level.

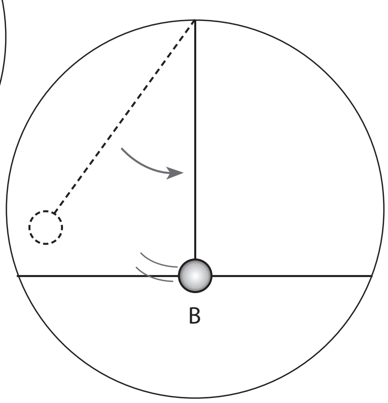
It gains gravitational potential energy as it is at a height above its original position, B.



② When the bob is released, it swings downwards, and the gravitational potential energy is converted to kinetic energy.

Since energy cannot be created or destroyed, the kinetic energy gained must have been converted from the gravitational potential energy lost.

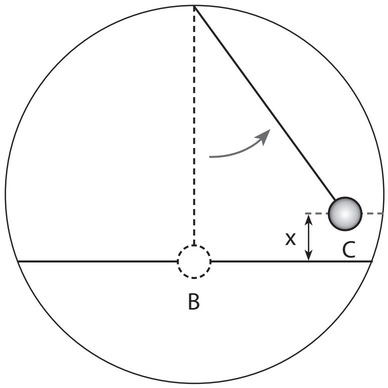
The swinging pendulum bob has maximum kinetic energy when it reaches B.

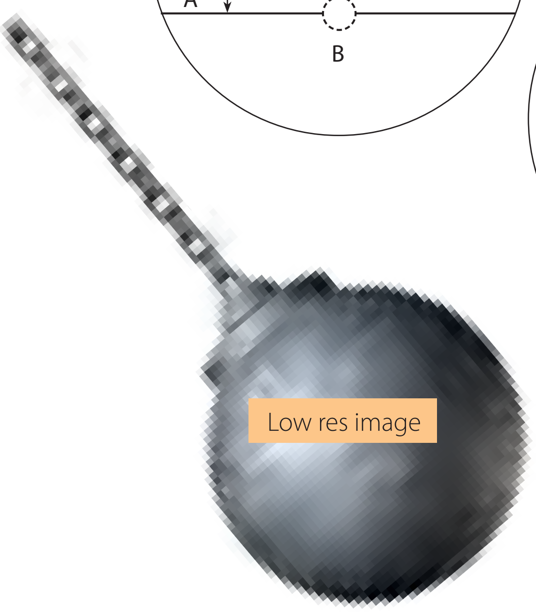


③ As the bob swings to the other side, its kinetic energy is converted back to gravitational potential energy.

The gravitational potential energy gained is converted from the kinetic energy lost. Thus, the pendulum bob slows down as it gains height.

At position C, where the height is maximum, it only has gravitational potential energy. This gravitational potential energy is converted to kinetic energy when it swings to its original position again at B.





Flow diagram:

Gravitational potential energy at A → Kinetic energy at B → Gravitational potential energy at C

WORD ALERT

Vice versa: the other way round (in this case: kinetic energy changing back to gravitational potential energy)

Conserved: kept the same

ENRICHMENT THINK

1 Using the principle of conservation of energy, work out an equation to show that the maximum speed of a swinging ideal pendulum is independent of the mass of the pendulum. What does the maximum speed depend on?

2 In the real world, a swinging pendulum will eventually come to a stop. Explain what happens in terms of energy conversion.

QUICK CHECK

In Worked Example 6C, the energy changes of the pendulum between points can be explained by the principle of conservation of energy.

True or false?

ENRICHMENT THINK

Refer to Figure 6.7. One of the explanations is scientifically correct.

In what way(s) are the other two explanations not scientifically correct?

Worked Example 6C

Figure 6.6 shows a pendulum of mass 0.4 kg oscillating in a vacuum. If P is the lowest position of the pendulum where its maximum speed is 1.5 m/s, calculate

(a) the maximum kinetic energy of the pendulum;

(b) the maximum gravitational potential energy of the pendulum as it rises to its greatest height at Q;

(c) the greatest height, h.

(Take $g = 10$ N/kg)

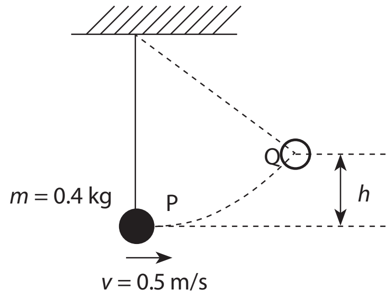


Figure 6.6

Solution

(a) Maximum kinetic energy at P $= \frac{1}{2}mv^2 = \frac{1}{2}(0.4)(1.5)^2 = 0.45$ J

(b) Loss of kinetic energy at P = gain in gravitational potential energy at Q.
Therefore, maximum gravitational potential energy at Q = 0.45 J

(c) Maximum gravitational potential energy $= mgh = 0.45$ J

$$\therefore h = \frac{0.45}{mg} = \frac{0.45}{(0.4)(10)} = 0.113 \text{ m}$$

(b) A robot waiter on the move

Have you been to a restaurant and had your food served by a robot waiter? Figure 6.7 shows a singing robot waiter with flashing lights moving across the floor. It is carrying a food tray. The robot uses electrical energy to perform its functions. What happens to the electrical energy inside the robot?

The three restaurant guests give their own explanations. Which explanation is scientifically correct?

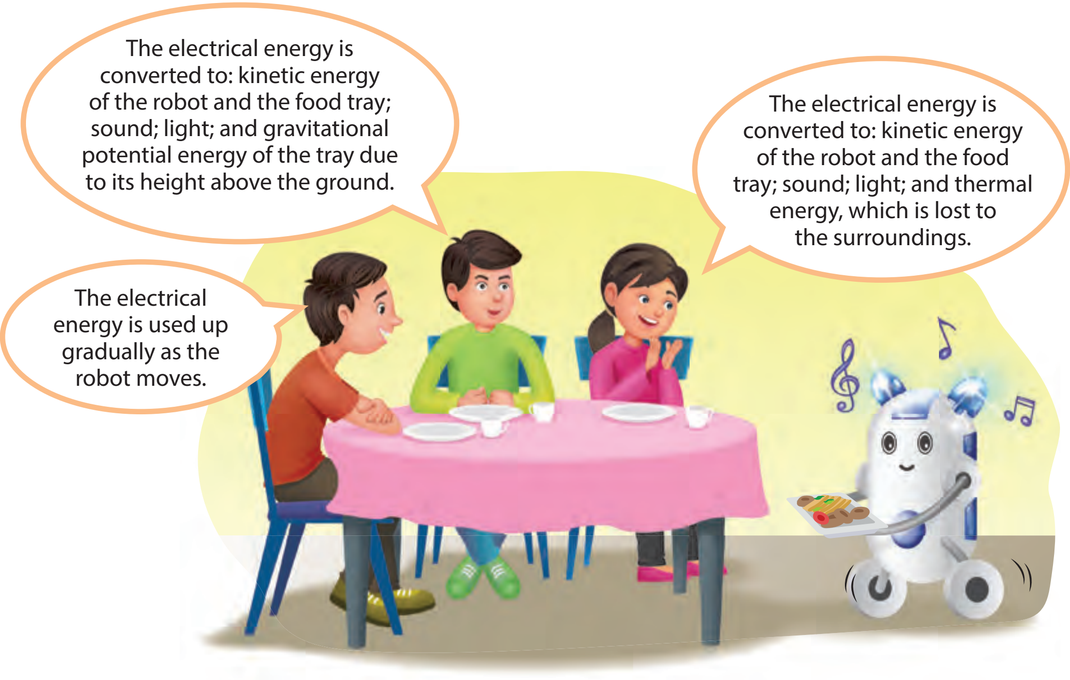
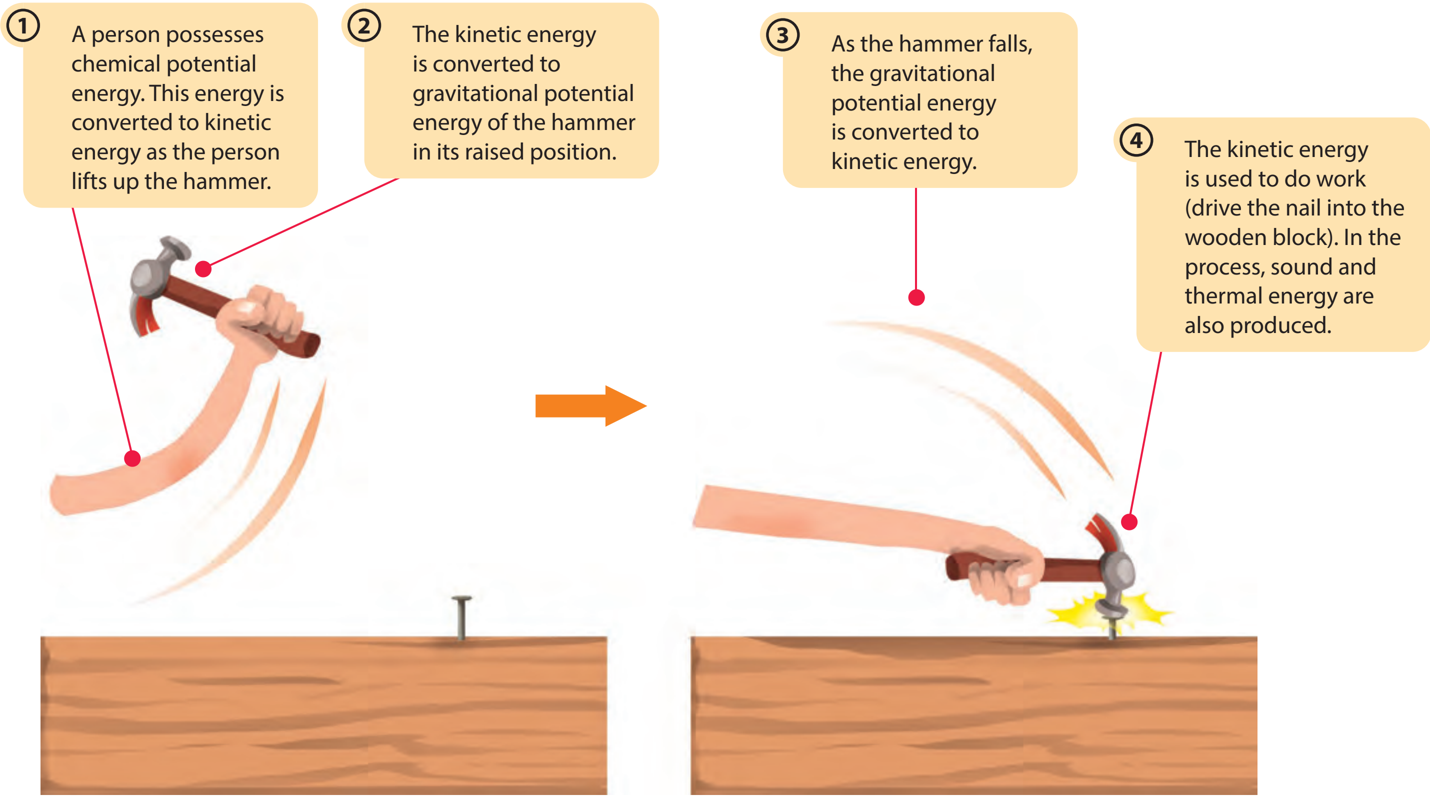


Figure 6.7 *What happens to the electrical energy used by the robot waiter?*

S

(c) Hammering a nail

Figure 6.8 shows the energy conversion when a nail is hammered. We can use a **Sankey diagram** to represent the energy conversion involving multiple stages. A Sankey diagram begins with the energy input on the left and branches out into useful energy output and wasted energy. The useful energy output branch points to the right and wasted energy branch points downwards.



Sankey diagram:

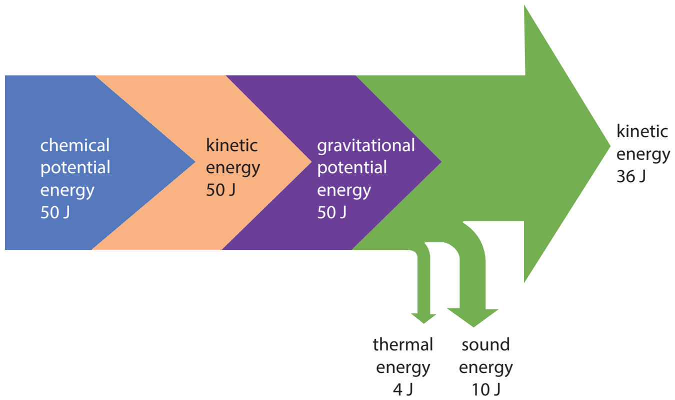


Figure 6.8 *Hammering a nail involves several energy conversions*

In the Sankey diagram above, chemical energy is the energy input which is first converted into kinetic energy, then into gravitational potential energy before being converted into other forms of energy. The final kinetic energy branch is the thickest since most of the energy is converted into it as useful output energy. The other two branches are much thinner because only small amounts of the energy are converted to sound and thermal energy as wasted energy.

In any event or processes that occur in the real world, not all the energy can be fully converted from one form to another. The energy tends to be dissipated, i.e., become more spread out among the objects and surroundings.

A-Z WORD ALERT

Dissipated: scattered, dispersed

Let's Practise 6.1

1 State the energy conversions that take place when
   (a) water is boiled using an electric kettle;
   (b) a light bulb is connected to a dry cell.

2 A ripe mango hangs from the branch of a tree. Using the principle of conservation of energy, explain what happens to the mango's gravitational potential energy when it falls to the ground.

3 A softball player throws a ball into the air and catches it on the way down. Ignoring the air resistance that acts on the ball, state the energy conversions that take place by means of a flow diagram.

4 S A 2.0 kg flower pot accidentally falls from a height of 45 m towards the ground. What is the
   (a) gravitational potential energy of the flower pot before the fall;
   (b) speed of the flower pot just before it hits the ground assuming negligible air resistance?
   (Take $g = 10$ N/kg)

5 S When a roller coaster is set in motion from a high place, its gravitational potential energy is converted to kinetic energy and other forms of energy.
   (a) How does the roller coaster first obtain its gravitational potential energy?
   (b) Since energy is conserved, why could the roller coaster not continue its motion perpetually?
   (c) Use a Sankey diagram to show how the principle of conservation of energy can be applied from the launching station of the roller coaster to the highest starting position.

6 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

WORD ALERT

Perpetually: continue without stopping

LINK

Exercises 6A–6B, pp. XX–XX

6.2 Work

In this section, you will learn the following:

- Understand that mechanical or electrical work done is equal to the energy transferred.
- Recall and use the equation for mechanical working, $W = Fd = \Delta E$.

LINK

Recall the concept of force that you have learnt in Chapter 4.

What is work done?

Look at Figure 6.9. What is the lady doing? What is the boy doing?

Both the lady and the boy are exerting force on objects. Is work being done in both situations?

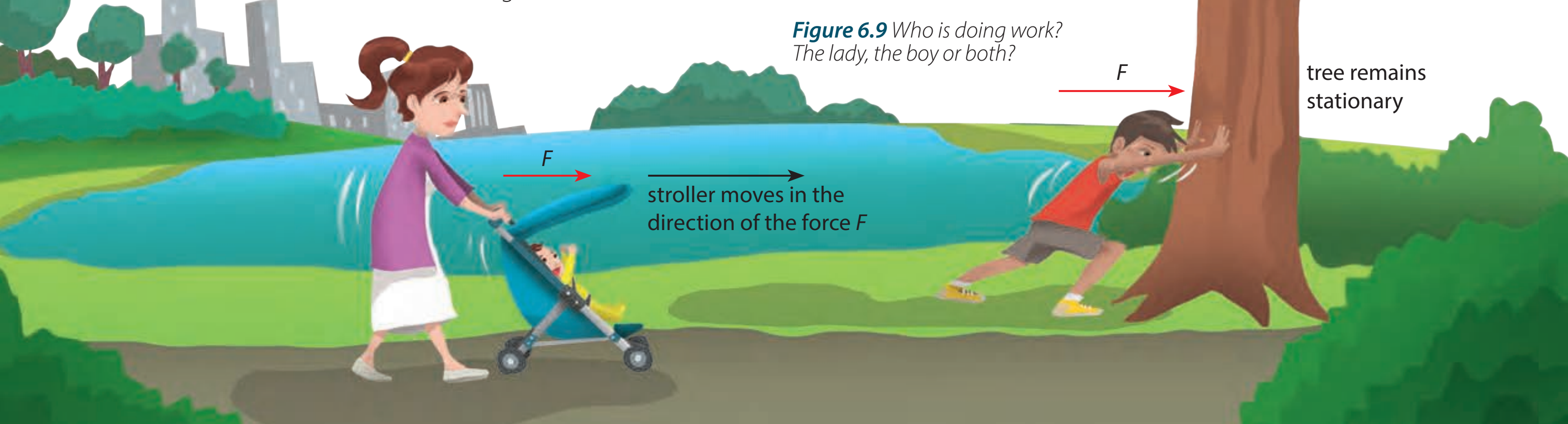


Figure 6.9 *Who is doing work? The lady, the boy or both?*

In physics, work is done only when an object moves under the influence of a force. Therefore, in Figure 6.9, the lady is doing work, but the boy is not.

Work done by a constant force on an object is the product of the force and the distance moved by the object in the direction of the force.

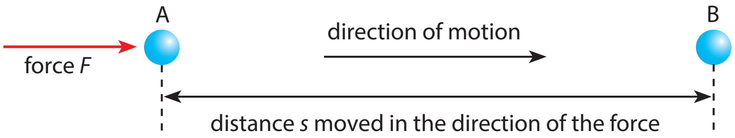


Figure 6.10 *Illustrating work done*

Using Figure 6.10, we can represent the work done W by the force F in moving the object from point A to point B with the following equation:

$W = F \times s$ where W = work done by a constant force F (in J)
F = constant force (in N)
s = distance moved by the object in the direction of the force (in m)

The SI unit of work is the **joule (J)**. Both work done and energy have the same unit — joule. This is because work done is equal to energy transferred. The work done by the lady in Figure 6.9 is equal to the energy transferred into kinetic energy of the stroller with the baby.

Recall the example of the robot waiter on page 88. Similarly, the work done by the robot is the measure of electrical energy which is transferred into kinetic energy, sound, light and thermal energy, which is lost to the surroundings.

From the equation, we can deduce the following:

One joule is the work done by a force of one newton, which moves an object through a distance of one metre in the direction of the force.

Worked Example 6D

A librarian pushes a trolley of books for shelving (Figure 6.11). The horizontal force F exerted by the librarian on the trolley is 8 N and the trolley moves a distance of 5 m in the direction of the force.

(a) Calculate the work done on the trolley.

(b) Explain what happened to the mechanical work done.

Solution

(a) Given: Force $F = 8$ N
Distance moved $s = 5$ m

Work done
$W = F \times s = 8 \text{ N} \times 5 \text{ m} = 40 \text{ J}$

(b) The mechanical work done by the force F in moving the trolley is transferred into kinetic energy of the trolley.

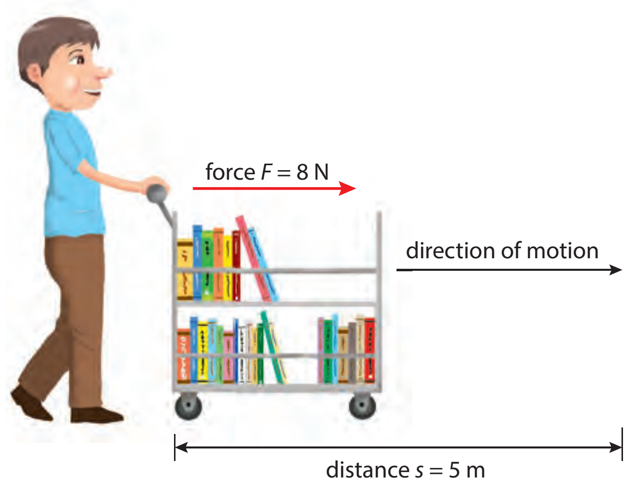


Figure 6.11

ENRICHMENT *INFO*

Another Real-world Example of No Work Done

A student is queuing at the library counter to borrow some books. He holds the books in a stationary position. While doing so, he balances the weight W of the books by exerting an upward force F of magnitude W. To check out the books, the student walks across a horizontal floor to the counter over a distance s.

Using the definition of work done, there is no work done by the upward force F. This is because the distance moved in the direction of force F is zero.

Worked Example 6E

The trolley of books pushed by the librarian in Worked Example 6D has a mass of 80 kg. After pushing the trolley over a horizontal distance, he reaches the bottom of a gentle incline with a certain speed *v*. The vertical height of the incline is 0.5 m. In order to maintain the same speed *v* up the incline, the librarian exerts a much larger force of 40 N to push the trolley over a distance of 10 m along the incline.

Assuming negligible air resistance and frictional effects at the moving parts of the trolley,

(a) calculate the work done by the 40 N force on the trolley along the incline;

(b) S calculate the gain in gravitational potential energy of the trolley.

(Take g = 10 N/kg)

Solution

Given: Mass m = 80 kg
Vertical height h = 0.5 m
Force F = 40 N
Distance moved along the incline, s = 10 m

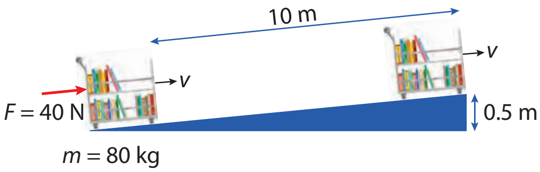


Figure 6.12

(a) Work done $W = F \times s$ = 40 N × 10 m = 400 J

(b) S Gain in gravitational potential energy = mgh = 80 kg × 10 N/kg × 0.5 m = 400 J

QUICK CHECK

Refer to Worked Example 6E. Work is done by the force of 40 N to push the trolley over a distance of 10 m up the incline at a constant speed. This work done is transformed into gain in gravitational potential energy of the trolley.

True or false?

Let's Practise 6.2

1 A mother carrying her baby in a stationary position does no work. Explain.

2 Define the joule.

3 A box is placed on a smooth floor. A force of 8.0 N acts horizontally on the box. The distance moved by the box in the direction of the force is 3.0 m.

(a) Calculate the work done by the force.

(b) Calculate the gain in the kinetic energy of the box.

5 A 50-N package is lifted 10 m vertically at a constant speed.

(a) Calculate the work done by the force of 50 N on the package.

(b) S Calculate the gravitational potential energy gained by the package.

6 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

Exercise 6C, pp. XX–XX

6.3 Energy Resources

In this section, you will learn the following:

- Describe how electricity or other useful forms of energy may be obtained.
- Describe advantages and disadvantages of the methods for obtaining energy.
- S Show an unde rstanding that energy is released by nuclear fusion in the Sun.
- S Know that research is being carried out to investigate how energy released by nuclear fusion can be used to produce electrical energy on a large scale.
- S Understand that the Sun is the source of energy for most of our energy.
- Show a qualitative understanding of efficiency.
- S Recall and use the equations:

$$\text{Efficiency} = \frac{\text{useful energy output}}{\text{energy input}} \times 100\%$$

$$\text{Efficiency} = \frac{\text{useful energy output}}{\text{power input}} \times 100\%$$

How can we obtain energy?

Figure 6.13 Jakarta looks beautiful at night. Large amounts of energy is used to light up the city.

We consume large amounts of energy every day to improve the quality of our lives. For example, we need electrical energy to run machines and to light up the lamps. We need chemical potential energy in petrol and diesel to drive cars and buses, and we need gas to cook food and heat water. A lot of energy is used to light up buildings and streets at night (Figure 6.13).

Examples of major energy resources

Major energy resources

We depend on some major energy resources to produce electricity and other useful forms of energy (Table 6.1). These energy resources have some advantages and disadvantages.

Table 6.1 Major energy resources

Energy resources and how useful forms of energy are produced	Advantages	Disadvantages
Fossil fuels • Examples of **fossil fuels** are petroleum, natural gas, coal and wood. • Chemical potential energy is stored in the structure of the atoms and molecules. • When the fuel is burnt in air, the atoms and molecules are regrouped due to a chemical reaction. • The chemical potential energy is converted mainly to thermal energy and light for cooking and heating purposes.	• Widely available at a large scale • Relatively cheaper in cost of production	• Environmental pollution from the gases, produced during burning, contributes to global warming • Non-renewable energy resource

Figure 6.14 Mining for coal

Table 6.1 Major energy resources [continued]

Energy resources and how useful forms of energy are produced	Advantages	Disadvantages
Biofuels • Examples of biofuels are ethanol, biodiesel and biogas, which are derived from biomass. Biomass comes from living materials such as corn, sugar cane, vegetable oils, animal fats and animal manure. • Chemical potential energy is stored in the biofuels. • The chemical potential energy is converted mainly to thermal energy and light for cooking and heating purposes.  **Figure 6.15** Biofuel plant on a farm processing cow dung to produce biogas	• Widely available at a large scale • Relatively cheaper in cost of production • Renewable energy source	• Environmental pollution from the gases produced during burning contributes to global warming
Hydropower • Water movement provides power to spin turbines to generate electricity. This hydropower or water power can be obtained from ocean waves, tides and water behind hydroelectric dams. • Water behind hydroelectric dams has gravitational potential energy. This energy is converted to kinetic energy by releasing the water and letting it flow downwards. The flowing water will cause the turbines to spin. • As the turbines spin, the kinetic energy of the turbines is converted to electrical energy by the generators connected to the turbines.  **Figure 6.16** Kurobe dam in Japan	• Clean method of producing cheap electricity • Renewable energy resource as the water movement can be continually regenerated	• High cost of building dams, turbines and generators • Damming a river for hydroelectric power station may cause damage to the environment surrounding the river
Geothermal energy • In certain areas, such as volcanic regions, geological forces push large amounts of hot molten rocks near the Earth's surface. These places are known as geothermal hotspots. • Water that makes its way to these geothermal hotspots is heated and subjected to great pressure. • This heated water contains a large amount of thermal energy. It is forced to the surface as boiling water and steam to drive turbines. • Electricity is produced by generators connected to the turbines.  **Figure 6.17** Geothermal power station in Iceland	• Clean source of naturally available thermal energy • Renewable energy resource	• Environmental pollution caused by the release of poisonous gases such as hydrogen sulphide into the atmosphere • Not widely available as they are found only in certain areas around the world

PHYSICS WATCH

Scan this page to watch a clip on how hydroelectric power is generated.

Table 6.1 Major energy resources [continued]

Energy resources and how useful forms of energy are produced	Advantages	Disadvantages
Solar energy • S Solar energy comes from the Sun. This energy is released in the Sun by nuclear fusion, where hydrogen atoms combine to form helium atoms. • Solar energy can be converted directly to electricity. Solar cells are used to change solar energy to electrical energy by means of photovoltaic effect. • The infrared electromagnetic waves in the solar energy can be converted to thermal energy, by means of a solar panel or collector with a blackened surface, for heating water. • Solar energy is the source of wind energy. The uneven heating of the Earth's surfaces (land, sea and air) results in the movement of warm and cold air. This produces wind. By means of wind electric generators, wind energy can be converted to electrical energy.	• Less polluting than fossil fuels • Renewable energy resource	• Not always available as there is no sunlight at night, and it is weather-dependent • Uses a lot of space
Nuclear energy • Nuclear fuels such as uranium are used to produce large amounts of thermal energy. • The thermal energy is used in boilers to heat up water into steam, which drives the turbines in the nuclear power station. • Electricity is produced by generators connected to these turbines.	• A low carbon energy resource which helps to reduce greenhouse gas emissions that cause global warming • Higher reliability in supplying uninterrupted power	• Risk of accidents and pollution from the improper disposal of radioactive wastes • Non-renewable energy resource as the amount of nuclear fuel is limited

Figure 6.18 Solar cells on a roof top harness energy from the Sun.

Figure 6.19 Uranium fuel rods inside a nuclear reactor

PHYSICS WATCH

Scan this page to watch a clip about how a food seller came out with an innovative idea to harness the Sun's energy.

Nuclear fusion reactors for the future

Nuclear fusion is a process where atomic nuclei of light elements combine to form heavier elements. The light elements are deuterium and tritium (isotopes of hydrogen).

Nuclear fusion is relatively safer than nuclear fission and there is plenty of deuterium in seawater. These have encouraged experimental research for many years to make a fusion nuclear reactor on a commercial scale. The energy released from nuclear fusion can be used to produce electrical energy on a large scale.

One promising multi-nation project is the International Thermonuclear Experimental Reactor (ITER) in southern France, to be launched in 2025.

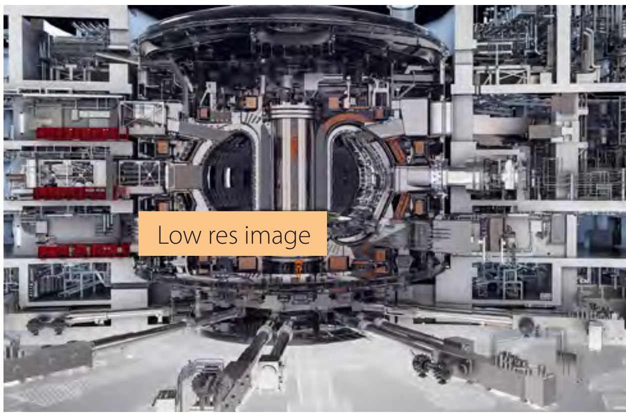


Figure 6.20 Model of ITER reactor

ENRICHMENT THINK

Refer to Table 6.1. Why is it most useful to produce electrical energy from the major energy resources?

The Sun as our main source of energy

Based on Table 6.1 on pages 93 to 95, why is radiation from the Sun considered to be the main source of energy for many of the energy resources?

Other than geothermal, nuclear and tidal energy resources, the other energy resources can be traced to the important role of solar energy from the Sun.

- Solar energy is the source of wind energy (see Table 6.1).
- Solar energy is converted to chemical potential energy in plants through photosynthesis. The survival of animals depends on the transfer of this energy through food chains. Fossil fuels come from the remains of plants and animals.
- Solar energy plays an important role in the water cycle. It evaporates water to bring fresh water in the form of rain and snow. These in turn are the sources for hydropower.

What is efficiency?

By the principle of conservation of energy, the total energy output of an ideal machine is equal to its total energy input. However, in reality, the useful energy output of a machine is always less than the energy input. Some energy is dissipated during the energy conversion due to friction. This energy usually takes the forms of thermal and sound energy. The energy that is lost to the surroundings is considered wasted energy output.

Based on the principle of conservation of energy,
total energy input = useful energy output + wasted energy output.

The efficiency of a machine can be calculated using the following formulae:

$$\text{Efficiency} = \frac{\text{useful power output}}{\text{energy input}} \times 100\%\ , \quad \text{Efficiency} = \frac{\text{useful power output}}{\text{power input}} \times 100\%$$

QUICK CHECK

Refer to Worked Example 6F.
The principle of conservation of energy can be used to explain the 70% of wasted energy output, namely thermal energy and sound energy.

True or false?

Worked Example 6F

A power station uses fossil fuel to generate electricity. What does it mean to say that the efficiency of the power station is only 30%?

Solution
The chemical potential energy in the fossil fuel makes up 100% of the total energy input.
Out of this 100%, only 30% is converted to useful energy output in the form of electrical energy.
The remaining 70% is wasted energy output.

Let's Practise 6.3

1 Give an example of a major source of energy that converts chemical potential energy into thermal energy.

2 Nuclear power stations are less polluting.
   (a) What is the name of the process in the production of nuclear energy?
   (b) State **one** disadvantage of using nuclear energy.

3 What does it mean to say that a solar cell has an efficiency of 45%?

4 Ⓢ A machine produces 35 J of useful output energy for every 50 J of total energy input. Calculate the efficiency of the machine.

5 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

Exercise 6D, pp. XX–XX

6.4 Power

In this section, you will learn the following:
- Define *power*.
- Recall and use the equation $P = \frac{W}{t} = \frac{\Delta E}{t}$ in simple systems.

WORD ALERT

Scenarios: settings, situations

What is power?

To explain what power is, we consider the two scenarios in Figure 6.21.

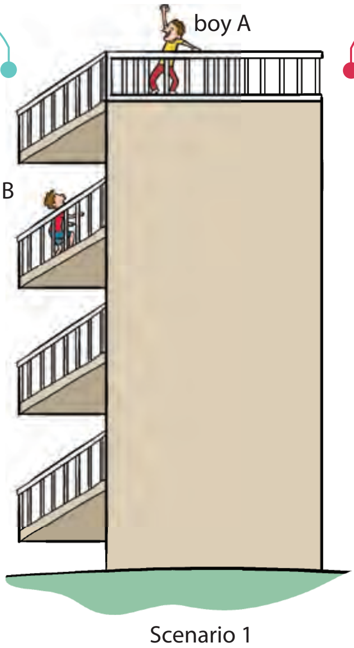
Two boys have to climb up the stairs as the lift is out of order.

Scenario 1

- Boy A and boy B have equal mass;
- Boy A reached the fourth storey before boy B.

The two boys are of equal mass and travel the same distance. Therefore, they do the *same amount of work*.

- However, since boy A took a *shorter time* to reach the fourth storey as compared to boy B, we say that *boy A has more power*.
- Boy A has more power than boy B because he can do the *same amount of work more quickly*.



Scenario 2

- Boy A has a larger mass than boy B;
- Boy A and boy B reached the fourth storey at the same time.

Since boy A has a larger mass, he has to do *more work* to carry himself up the four storeys.

- In other words, boy A is able to do *more work* than boy B in the *same amount of time* as boy B.
- Therefore, we say boy A has *more power*.

Figure 6.21 *The amount of work done by the boys and the time taken to do the work determine who has more power.*

Power is defined as the work done or energy transferred per unit time.

The SI unit of power is the **watt (W)**. One watt is defined as the work done or energy transferred of one joule per second, i.e., 1 W = 1 J/s.

In equation form, $\boldsymbol{P = \frac{W}{t} = \frac{\Delta E}{t}}$ where P = power (W)

W = work done (J)

ΔE = energy converted (J)

t = time taken (s)

LINK

Practical 6A, pp. XX–XX

Note that the product of power P and time taken t tells us the amount of work done or the amount of energy being converted from one form to another.

ENRICHMENT ACTIVITY

Flying Wheel Toy

This activity will help you visualise the concept of power $P = \frac{W}{t} = \frac{F \times s}{t}$

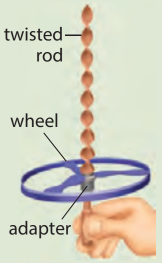


Figure 6.23 *Wheel toy*

Experiment A

1 Launch the wheel by pushing the adapter vertically upwards across the length of the rod as hard as possible.
2 Observe the maximum height that the wheel is able to fly up to.

Experiment B

1 Cut the twisted length of the rod into half.
2 Repeat the steps in Experiment 1.

Questions

1 Which of the maximum heights is higher?
2 Which experiment shows that a greater amount of work is done?
3 In which experiment is the launching power greater, assuming the time taken is the same?

Worked Example 6G

Eugene, who weighs 450 N, runs up ten steps. Each step is 0.20 m high. Calculate Eugene's power if he takes five seconds to run up the steps at a constant speed.

Solution

The upward force F exerted by Eugene's muscles to balance his weight = 450 N

The upward distance s moved by Eugene = height of steps = 0.20 m × 10 = 2.0 m

Using $W = F \times s$, work done W by Eugene = 450 N × 2.0 m = 900 J

Using $P = \frac{W}{t}$, Eugene's power = $\frac{900 \text{ J}}{5 \text{ s}} = 180$ W

Worked Example 6H

A filament lamp, rated at 40 W, converts 10% of its electrical energy supply to light energy. Calculate the quantity of light energy given off in five minutes.

Solution

Given: Power $P = 40$ W
Time $t = 5 \times 60 \text{ s} = 300$ s

Energy used by lamp in five minutes = $P \times t = 40 \text{ W} \times 300 \text{ s} = 1.2 \times 10^4$ J

Since 10% of this energy is converted to light energy, the amount of light energy given off in five minutes

$= \frac{10}{100} \times 1.2 \times 10^4$ J

$= 1.2 \times 10^3$ J

= 1.2 kJ

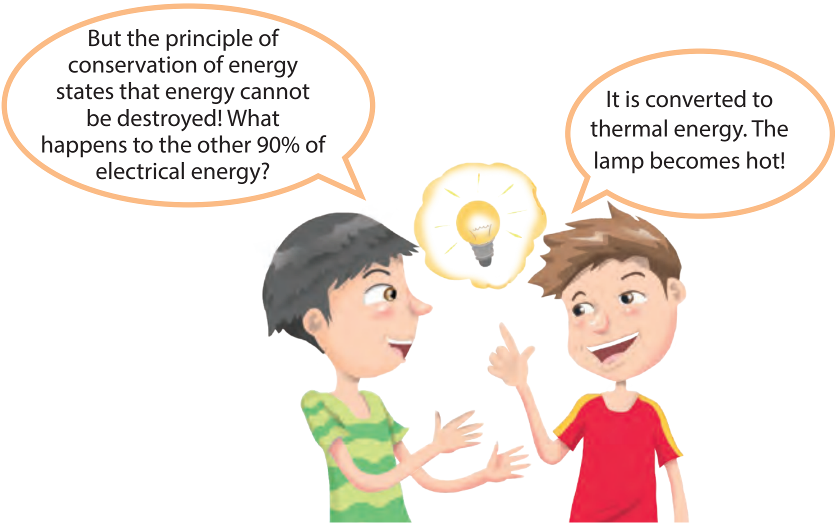


Figure 6.22

Let's Practise 6.4

1 Define the terms power and watt.
2 Calculate the power involved when a force of 50 N moves an object through a distance of 10 m in 5 s.
3 An electric motor in a washing machine has a power output of 1.0 kW. Calculate the work done in half an hour.
4 The same amount of water was poured into two electric kettles, one rated at 500 W and the other at 1000 W. Compare the time taken for both kettles to boil the water.
5 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

Exercises 6E-6G, pp. XX–XX
Exercise 6F Let's Reflect, p. X

Let's Map It

ENERGY E
(SI unit: J)

is the capacity to do

WORK W
(SI unit: J)

are related to

POWER P
(SI unit: W)

ENERGY is governed by

The principle of conservation of energy

states that

Energy cannot be created or destroyed but can be converted from one form to another.

examples of forms of energy

- **Potential energy**
  - Chemical potential energy
  - Elastic (strain) energy
  - Electrostatic potential energy
  - Magnetic potential energy
  - Nuclear energy
  - Gravitational potential energy
  - S $E_p = mgh$
- **Kinetic energy**
  - S $E_k = \frac{1}{2}mv^2$
  - Electrical energy
  - Thermal energy
  - Light
  - Sound

produced from major energy resources

- Fuel
- Biofuel
- Water
- Geothermal resources
- Nuclear fission
- Sun
  - – energy release by nuclear fusion
  - – S source of most of our energy
- Wind

WORK is defined as

S $W = F \times s$
where
F = force
s = distance moved in the direction of the force

POWER is defined as

S $P = \frac{W}{t} = \frac{E}{t}$
where
W = work done
E = energy converted

converted into useful energy by machines depending on their

Efficiency

- Where some of the energy input is converted to useful energy and some into wasted energy such as heat and sound
- S Can be calculated using the following formulae:

$$\text{Efficiency} = \frac{\text{useful energy output}}{\text{total energy input}} \times 100\%$$

$$\text{Efficiency} = \frac{\text{useful power output}}{\text{total energy input}} \times 100\%$$

Let's Review

(Take g = 10 N/kg)

Section A: Multiple-choice Questions

1 A car screeches to a stop to avoid colliding with a van. Assuming that the road is level, what energy changes have occurred?
- **A** Kinetic energy → thermal energy
- **B** Kinetic energy → sound energy
- **C** Kinetic energy → light and sound energy
- **D** Kinetic energy → sound and thermal energy

2 S A 0.8 kg brick is accidentally dropped from a building. It reaches the ground with a kinetic energy of 240 J. How tall is the building?
- **A** 19 m **B** 30 m
- **C** 192 m **D** 300 m

3 What is the work done by a force of 6.0 N acting horizontally on a body of mass 4.0 kg if the distance moved in the direction of the force is 3.0 m?
- **A** 2 J **B** 12 J
- **C** 18 J **D** 24 J

4 Which of the following energy resources is the odd one out?
- **A** Nuclear energy **B** Geothermal energy
- **C** Wind energy **D** Solar energy

5 A machine is able to lift 200 kg of bricks vertically up to a height of 30 m above the ground in 50 s. What is the power of the machine?
- **A** 0.12 kW **B** 1.2 kW
- **C** 6.0 kW **D** 300 kW

Section B: Short-answer and Structured Questions

1 A cyclist pedals up to the top of a hill.
- **(a)** What kind of energy is being used to do work against gravity?
- **(b)** State the type of energy the cyclist has when he stops at the top of the hill.
- **(c)** When the cyclist moves downhill without pedalling, what type of energy does he gain?

2 Energy cannot be created or destroyed.
- **(a)** State **one** example to show this and explain.
- **(b) (i)** Name **three** sources of non-renewable energy.
  - **(ii)** Suggest **two** things that you can do to help reduce the use of non-renewable energy.

3 S A simple pendulum consists of a string of length 50.0 cm and a pendulum bob of mass 10 g. The string hangs vertically from a fixed point O with the pendulum bob attached to its lower end at point P (Figure 6.24).

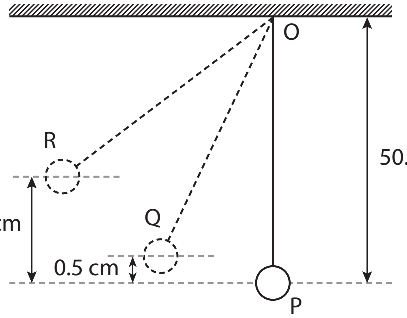


Figure 6.24

The pendulum bob is displaced to point R, 2.0 cm above P and released from rest. Assuming air resistance is negligible, calculate the
- **(a)** gain in potential energy of the pendulum bob at point R;
- **(b)** kinetic energy of the bob at point Q, 0.5 cm above P.

4 S A model car of mass 1.5 kg, with a string attached to its front end, is placed on a slope (Figure 6.25). A force of 10 N is applied on the string to move the car up the slope at a constant velocity. The force is applied in a direction that is parallel to the slope.

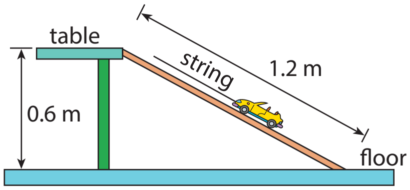


Figure 6.25

(a) With the aid of a diagram, describe how the force in the string can be measured.

(b) Calculate

(i) the gain in the car's potential energy as it moves from the floor to the table;

(ii) the work done by the force as it moves the car up the slope from the floor to the table;

(iii) the efficiency of this arrangement to raise the car.

5 S A roller coaster train at an amusement park has a mass of 1500 kg. It descends from point P, which is 30 m above ground, to point Q, which is 10 m above ground.

(a) Calculate the loss in the gravitational potential energy of the train when it moves from point P to point Q.

(b) If 20% of the gravitational potential energy lost is dissipated, calculate the

(i) kinetic energy of the train at point Q;

(ii) speed of the train at point Q.

(c) By means of a Sankey diagram, show the energy conversion between point P and point Q.

6 S The energy input and useful energy output (i.e. electricity) for five power stations were measured. The results are listed in Table 6.2.

Table 6.2

Power station	Energy input/10^{14}J	Useful energy output/10^{13}J
P	10.8	32.8
Q	17.1	21.3
R	2.5	10.1
S	2.1	7.5
T	2.0	4.1

(a) Each of the stations uses a different method to produce electricity.

(i) Calculate the efficiency of each power station.

(ii) If you had to build a power station, which power station would you choose to base the design of your power station on? Why?

(b) Assuming that the values in Table 6.2 are the energy outputs of each power station per day, what is the power generated by power station S?

(c) Why is there a difference between the energy input and useful energy output?

CHAPTER

7 Pressure

PHYSICS WATCH

Scan this page to watch a clip of everyday examples that are related to pressure.

The phrase 'to walk on eggs' means to be extra careful. Well, you certainly need to be extra careful in order not to break the eggs when walking on them. Yes, it is possible to stand or walk on eggs without breaking them. Have you ever tried it yourself?

The picture shows a person wearing sports shoes stepping on some eggs. The eggs did not break. The eggs would break easily if a person wearing high-heeled shoes were to step on them. This is because the pressure that acts on the eggs is much greater for a person wearing high-heeled shoes compared to a person wearing sports shoes.

QUESTIONS

- How do you think pressure is related to area?
- Is the pressure you feel when taking an exam the same kind as the pressure exerted onto the eggs?

7.1 Pressure

In this section, you will learn the following:

- Define *pressure*.
- Recall and use the equation $p = \frac{F}{A}$.
- Describe how pressure varies with force and area using everyday examples.

What is pressure?

In Chapter 4, you have learnt about the effects of forces. Pressure is an effect of a force on a surface. When a force presses onto a surface, it **exerts** a pressure on the surface. To measure this effect, we define it using quantities that we can measure.

WORD ALERT

Exerts: applies, puts

Pressure is defined as force per unit area. Its SI unit is **pascal (Pa)**.

In equation form, $\boldsymbol{p = \frac{F}{A}}$ where p = pressure (in Pa)
F = force (in N)
A = area (in m^2)

When the force is measured in newton (N) and the area in square metres (m^2), the pressure is newton per square metres (N/m^2). The unit N/m^2 is known as pascal (Pa) in the SI system of units. Square metres (m^2) is a big quantity. Often, the smaller unit square centimetres (cm^2) is used. When the area expressed is in cm^2, pressure is measured in N/cm^2.

ENRICHMENT ACTIVITY

Psi and *bar* are two common units used to measure pressure.

Use the Internet to find out

(a) the difference between the two units;

(b) the situations in which they are used.

Worked Example 7A

Figure 7.1(a) shows a woman weighing 600 N standing in high heeled shoes.

(a) If the total area of her soles and the heels in contact with the floor is 0.03 m^2, calculate the pressure the woman exerts on the floor.

(b) The area of each heel is 0.00030 m^2. Calculate the pressure the heel exerts on the floor when the woman is standing on one leg as shown in Figure 7.1(b).

(c) Compare the two values of pressure in (a) and (b). How is pressure related to area?

(a) **(b)**

Figure 7.1

Solution

(a) Given: Weight of the woman, F = 600 N
Area of contact, A = 0.03 m^2

By definition, pressure exerted by the woman on the floor

$$p = \frac{F}{A} = \frac{600\ \text{N}}{0.03\ \text{m}^2} = 20\,000\ \text{N/m}^2 = 2.0 \times 10^4\ \text{Pa}$$

(b) Given: When balancing on one heel, area of contact, A = 0.0003 m^2

$$p = \frac{F}{A} = \frac{600}{0.0003} = 2\,000\,000\ \text{N/m}^2 = 2.0 \times 10^6\ \text{Pa}$$

(c) The pressure in **(b)** is 100 times larger than in **(a)** due to the vastly different contact areas with the ground. When the same force is applied due to a smaller area, the pressure exerted is greater.

Figure 7.2 shows how pressure varies with force and pressure.

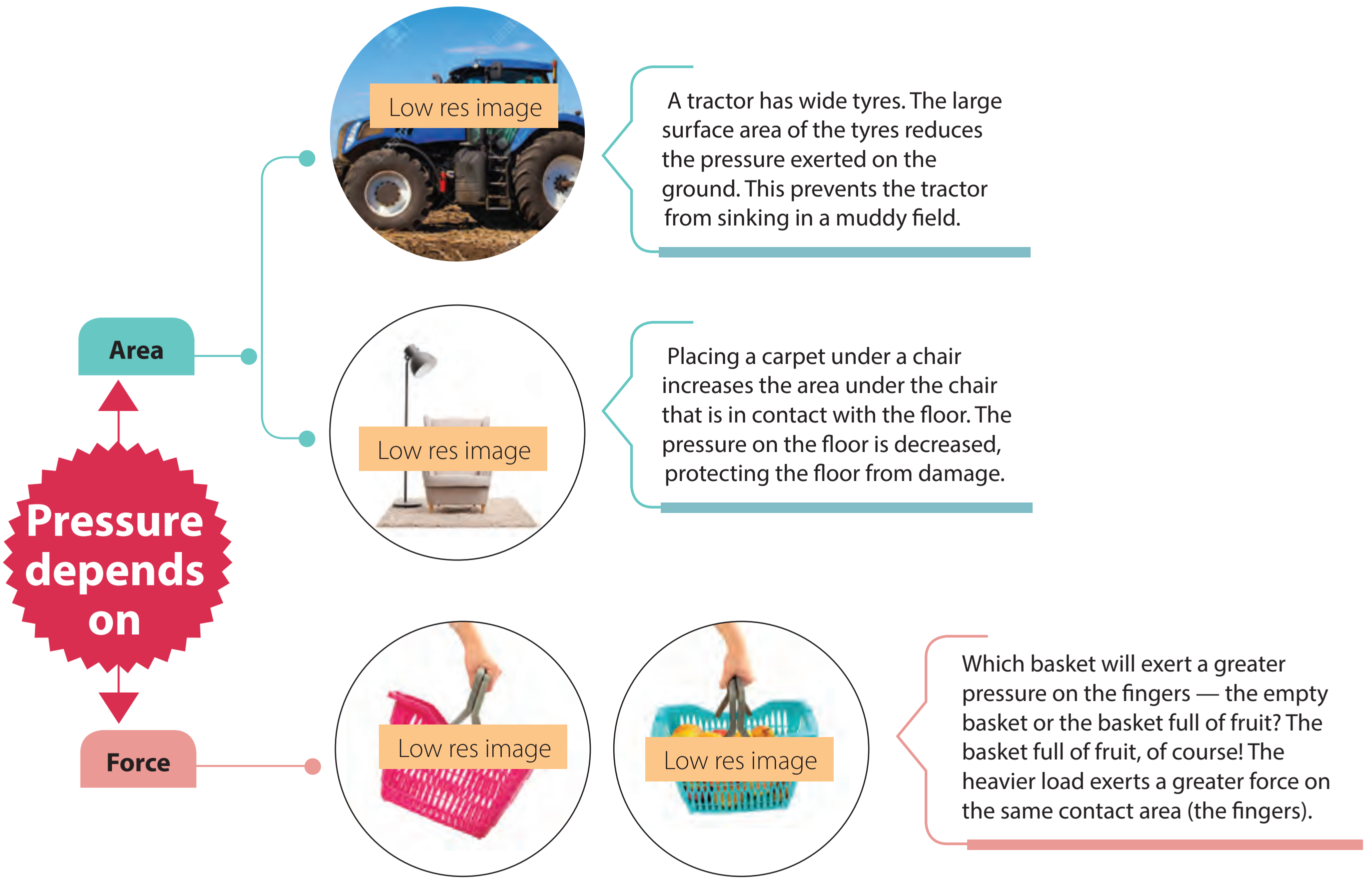


Figure 7.2 *Pressure depends on area and force.*

LINK

Recall the definition of weight from Chapter 3.

The examples of a woman wearing high-heeled shoes, a tractor with wide tyres, and placing a carpet under a chair shows that the force on a surface is due to the weight of objects resting on the surface. However, force can also be exerted by our hands.

Study Figure 7.3 and Figure 7.4. Why does a sharp knife cut more easily than a blunt one? Why is it easy to drive a nail into wood using a hammer?

A sharp knife has a smaller contact surface compared to a blunt one. So, a smaller force is required to exert the same amount of pressure to cut the tomato. Similarly, the head of the nail has a surface area many times bigger than the pointed end of the nail. The force exerted by the hammer is transferred to the pointed end. The pressure at the pointed end is many times bigger than at the head. The high pressure pushes the nail into the wood.

Figure 7.3 *Cutting tomatoes using a sharp kitchen knife*

Figure 7.4 *Driving a nail into a wood using a hammer*

Worked Example 7B

Figure 7.5 shows a block of dimensions 20 cm × 10 cm × 5 cm. The density of the block is 2.0 g/cm³.

(a) What is the weight of the block? (Take $g = 10$ N/kg.)

(b) On which face must the block rest to exert the greatest pressure? Calculate this pressure.

(c) On which face must the block rest to exert the least pressure? Calculate this pressure.

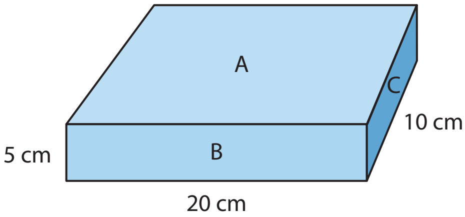


Figure 7.5

Solution

(a) Volume of the block, $V = 5 \text{ cm} \times 10 \text{ cm} \times 20 \text{ cm} = 1000 \text{ cm}^3$
Mass of the block, m = density × volume $= 2.0 \text{ g/cm}^3 \times 1000 \text{ cm}^3 = 2000 \text{ g} = 2 \text{ kg}$
Weight of the block $= mg = 2 \text{ kg} \times 10 \text{ N/kg} = 20 \text{ N}$

(b) The force exerted by the block is its weight, i.e., $F = 20$ N.
The pressure is the greatest when the area is the smallest.
So the block exert the greatest pressure when it is resting on face C.
Area of face C $= 5 \text{ cm} \times 10 \text{ cm} = 50 \text{ cm}^2$
$\therefore$ Pressure exerted by face C $= \dfrac{F}{A} = \dfrac{20 \text{ N}}{50 \text{ cm}^2} = 0.4 \text{ N/cm}^2$

(c) The pressure is the least when the area is the largest. This is when the block is resting on face A.

(d) Area of face A $= 10 \text{ cm} \times 20 \text{ cm} = 200 \text{ cm}^2$
$\therefore$ Pressure exerted by face A $= \dfrac{F}{A} = \dfrac{20 \text{ N}}{200 \text{ cm}^2} = 0.1 \text{ N/cm}^2$

QUICK CHECK

The greater the force exerted on the same contact surface area, the greater the pressure.

True or false?

LINK

PWB

Practical 7, p. XX–XX

Let's Practise 7.1

1 Write out the word equation for pressure.

2 Complete Table 7.1.

Table 7.1

Force /N	Area /m²	Pressure / Pa
1200	0.5	
	0.08	2000
800		50 000

3 A polystyrene cube of mass 5.0 kg is placed on a horizontal surface. The pressure due to the cube is 89 N/m².

(a) What is the force exerted on the surface? (Take $g = 10$ N/kg.)

(b) What is the area of contact between the cube and the surface?

(c) What is the length of the sides of the cube?

Figure 7.6

4 Look at Figure 7.6. Would the table make a deeper mark on the carpet if it is standing upright, or if it is turned upside-down? Explain your answer.

5 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK

TWB

Exercise 7A, pp. XX-XX

7.2 Pressure in Liquids

In this section, you will learn the following:

- Describe qualitatively how the pressure beneath the surface of a liquid changes with depth and density of the liquid.
- S Recall and use the equation $\Delta p = \rho g \Delta h$ for the change in pressure in a liquid.

A diver experiences pressure from the seawater (Figure 7.7). The deeper the diver dives, the greater the pressure. Why?

You have learnt that pressure is force per unit area. The force acting on the diver is due to the weight of the seawater pushing down on the diver. As the diver goes deeper, there is more water above the diver. When the diver dives deeper, the weight of the water pressing on the diver increases. The force on the diver increases. And so, the pressure increases.

Figure 7.7 *A scuba diver experiences pressure from the seawater.*

How does depth affect pressure in a liquid?

In Figure 7.8, a tall container with holes at different depths is used to show that water pressure increases with depth. The water spurts out furthest and fastest from the bottom hole. This shows that the pressure is greatest at the bottom of the container.

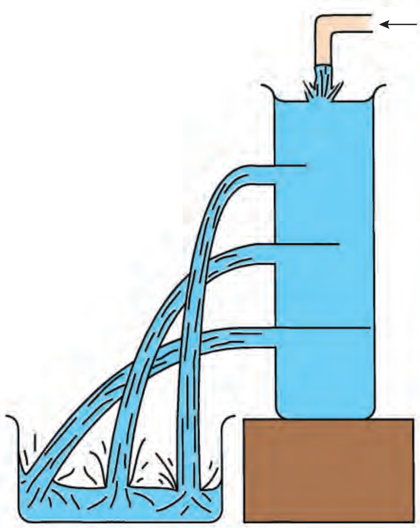


Figure 7.8 *Apparatus to show that water pressure increases with depth*

ENRICHMENT INFO

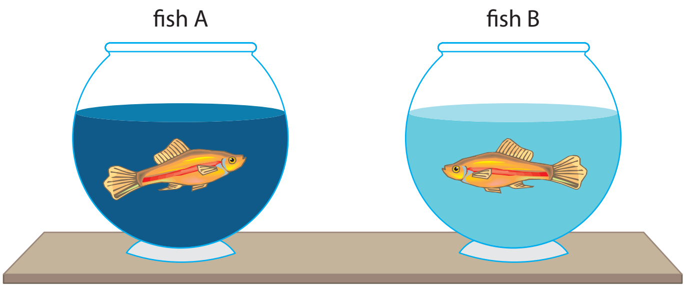
How Do Deep-sea Fish Survive Under Pressure?

Fish that live deep under the sea experience great pressure. At 3000 m or more below the sea surface, the amount of pressure would crush a body that contains air. This is because air can be compressed.

Fish that live nearer the sea surface have air sacs to help them float up or sink down in the water. Deep-sea fish do not have air sacs, so they do not get crushed under pressure.

How does the density of a liquid affect the pressure it exerts?

Recall that for a fixed volume of substance, mass, and therefore, weight increases with density. Figure 7.9 shows two fishbowls, each containing a fish and an equal volume of water. One fishbowl is filled with seawater and the other is filled with tap water. Seawater is more dense than tap water. Which fish experiences a greater pressure?



▲ Fishbowl filled with seawater ▲ Fishbowl filled with tap water

Figure 7.9 *Two liquids of different densities will exert different amounts of pressure.*

The two fish experience different amounts of pressure depending on the density of the water. For the same volume, the weight of seawater is greater than the weight of tap water. Thus, fish A experiences a greater pressure compared to fish B.

We have seen how depth and density affects pressure in a liquid. Therefore, we can conclude the following:

Pressure in a liquid increases with **depth** and **density**.

Worked Example 7C

Figure 7.10 shows four identical containers filled with the same amounts of liquids. Two of the containers contain liquid X and the other two contains liquid Y.

(a) At which point, A or B, is the pressure greater? Explain.

(b) The pressure at C is greater than the pressure at B. What can you conclude from this?

(c) Compare the pressure at A and the pressure at D.

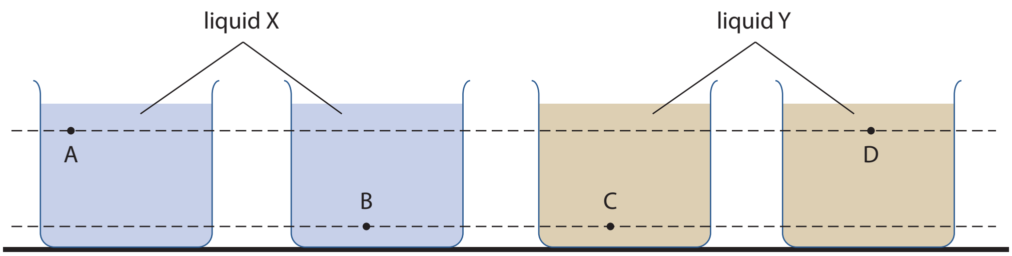


Figure 7.10

Solution

(a) The pressure at B is greater than at A. Liquid pressure increases with depth.

(b) Liquid pressure increases with density. This means liquid Y is more dense than liquid X.

(c) The pressure at A is lesser than the pressure at D.

LINK

Recall how density of a substance depends on its mass and volume from Chapter 5.

QUICK CHECK

Figure 7.11 shows two beakers containing water. The pressure at point P is greater than the pressure at point Q.

True or false?

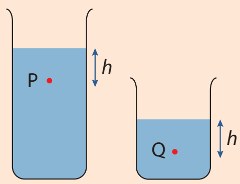


Figure 7.11

Calculating liquid pressure

Figure 7.12 shows a column of liquid. How can we calculate the change in liquid pressure from depth h_1 to depth h_2?

As we go deeper down the liquid column, the pressure increases because there is more liquid pressing down. This increase or change in pressure can be calculated by considering the additional force due to the additional weight of liquid.

Based on Figure 7.12,

Volume of the liquid = base area × height = $A\Delta h$
Mass of the liquid = density × volume = $\rho A \Delta h$

The additional force, ΔF, exerted by the additional liquid on area A, is the same as the weight W of the liquid. This weight is given by $W = mg$.

Earlier, you have learnt that $p = \frac{F}{A}$.

So, $\Delta p = \frac{\Delta F}{A} = \frac{W}{A} = \frac{mg}{A} = \frac{\rho A \Delta h g}{A} = \rho g \Delta h$

Thus, the change in pressure in a liquid is given by the following equation:

Δp = ˝g Δh

Based on the equation above, it is clear that the pressure due to a liquid increases with density and depth.

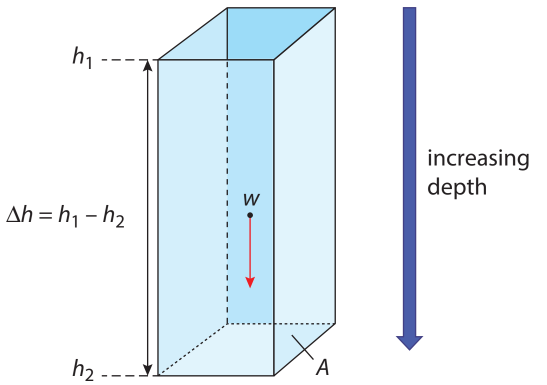


Figure 7.12 *Liquid column of height h, base area A and density ρ*

HELPFUL NOTES

- Depth is measured as height from the surface of the liquid.
- The Greek letter ρ (pronounced as *rho*) is used to represent density of a liquid.

Worked Example 7D

Figure 7.13 shows a small submarine submerged below the surface of the sea. The density of seawater is 1030 kg/m³ and the gravitational field strength is 10 N/kg.

(a) The submarine moves from the surface of the sea to a depth as shown in the diagram. Calculate the change in pressure experienced by the submarine.

(b) The submarine changes its depth. This causes the pressure exerted on it to change by 0.10 MPa. Calculate the change in depth of the submarine.

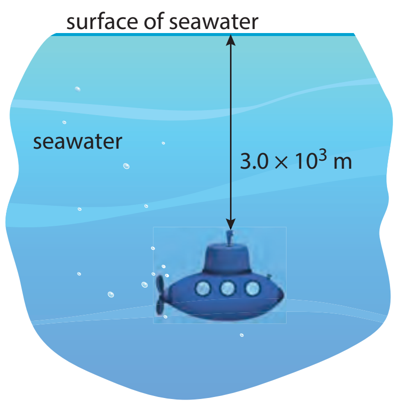


Figure 7.13

WORD ALERT

Submerged: made to sink

Solution

(a) Change in depth of the submarine, $\Delta h = 3.0 \times 10^3$ m

Change in pressure, $\Delta p = \rho g \Delta h$

$= 1030 \text{ kg/m}^3 \times 10 \text{ N/kg} \times 3.0 \times 10^3 \text{ m}$

$= 3.09 \times 10^7$ Pa or 30.9 MPa

(b) From $\Delta p = \rho g \Delta h$, change in depth is $\Delta h = \dfrac{\Delta p}{\rho g}$

When $\Delta p = 0.10 \text{ MPa} = 0.10 \times 10^6$ Pa,

$$\Delta h = \frac{0.10 \times 10^6 \text{ N/m}^2}{1030 \text{ kg/m}^3 \times 10 \text{ N/kg}}$$

$= 9.7$ m

Note that the actual pressure acting on the submarine is the sum of the pressure due to the seawater and the air pressure at the surface of the water.

Let's Practise 7.2

1 When an object is immersed in a liquid, the liquid exerts pressure on the object. Give **two** factors that affects this pressure.

2 Fill in the blanks with the word *greater* or *less*.

(a) The pressure at the bottom of a swimming pool is ________ than the pressure near the surface of the pool.

(b) Oil is less dense than water. The pressure at the bottom of a bottle of oil is ________ than the pressure at the bottom of an identical bottle of water.

3 Write the equation for the change in pressure beneath a liquid surface.

4 A marine biologist dives into the sea to observe marine life. What change in pressure does she experience when she is 5 m below the surface of the sea?

(Take density of seawater = 1025 kg/m^3 and $g = 10$ N/kg.)

5 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

QUICK CHECK

Consider a column of liquid. The pressure at any point in the liquid depends only on the height of the liquid above it.

True or false?

WORD ALERT

Immersed: dipped

LINK

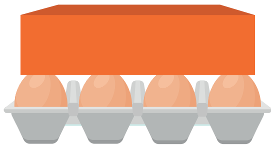
Exercises 7B–7C, pp. XX–XX

Exercise 7D Let's Reflect, p. XX

Let's Map It

PRESSURE
(SI unit: Pa)

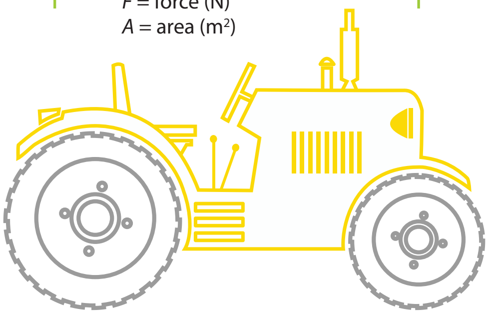
is defined as



Force per unit area

$p = \frac{F}{A}$

where
p = pressure (Pa or N/m^2)
F = force (N)
A = area (m^2)



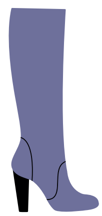
depends on

Force

- For the same area, the greater the force, the greater the pressure.

Area

- For the same force, the smaller the area, the greater the pressure.



example

Pressure in liquids

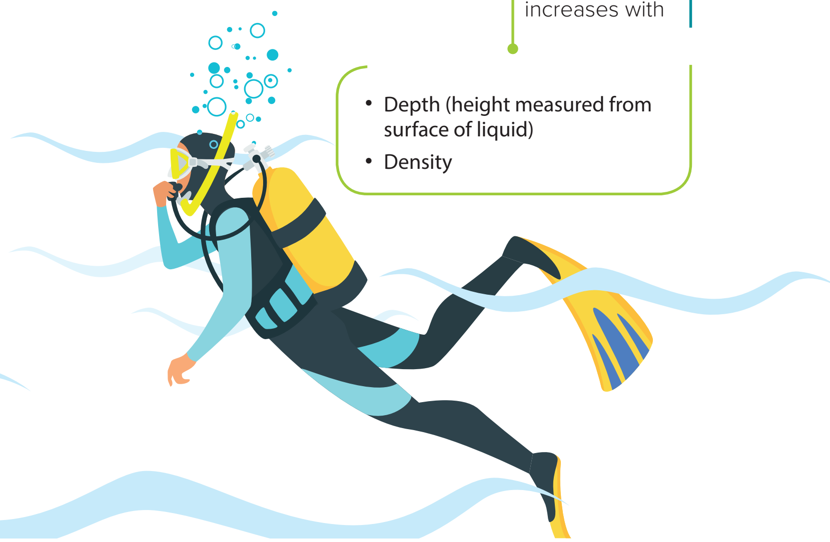
increases with

- Depth (height measured from surface of liquid)
- Density

S Change in pressure is given by

$\Delta p = \rho g \Delta h$

where
ρ = density of liquid (kg/m^3)
g = gravitational field strength (N/kg)
h = height of liquid column (m)



Let's Review

Section A: Multiple-choice Questions

1 Which of the following statements define pressure?

A force × depth B force × area

C $\frac{\text{force}}{\text{area}}$ D $\frac{\text{force}}{\text{depth}}$

2 Figure 7.14 shows a box on a table. The weight of the box is 50 N. What is the pressure exerted on the table by the box?

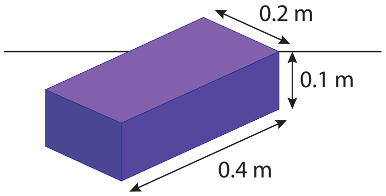


Figure 7.14

A 0.4 Pa B 5 Pa

C 500 Pa D 625 Pa

3 (S) A diver dives deeper into the sea. She experiences a change in pressure of 1.03×10^5 Pa exerted by the seawater. What is her change in depth? (Take density of seawater = 1030 kg/m^3 and g = 10 N/kg.)

A 1 m B 5 m

C 10 m D 50 m

Section B: Short-answer and Structured Questions

1 Figure 7.15 shows a girl exercising. The pressure she exerts on the floor in position A is different to that in position B. Explain why.

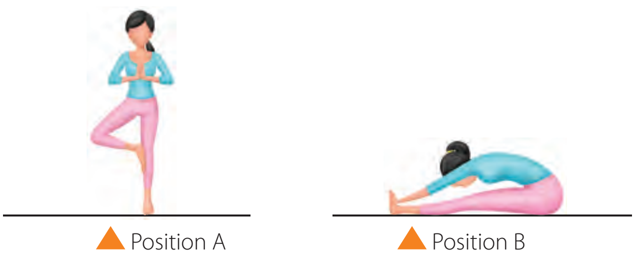


Figure 7.15

2 Figure 7.15 shows a ball bearing sinking in oil inside a measuring cylinder.

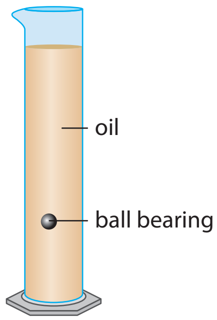


Figure 7.16

(a) Describe how the pressure on the ball bearing changes as it sinks in the oil.

(b) The oil in the measuring cylinder is replaced with an equal volume of water. Water is more dense than oil. Would the change in pressure exerted on the ball bearing be greater in water than in oil as it moves down the container? Explain your answer.

3 (S) Figure 7.17 shows a container of liquid on a table. The density of the liquid is 880 kg/m^3. The base area of the container is 0.02 m^2. The total mass of the container with the liquid inside is 5 kg. Gravitational field strength is 10 kg/N.

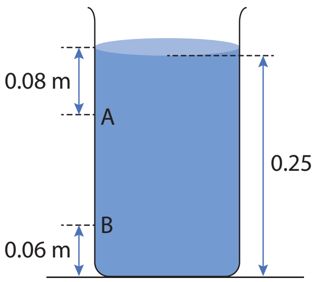


Figure 7.17

(a) Calculate the pressure exerted on the table by the container of liquid?

(b) An object is lowered into the liquid. Calculate the change in pressure experienced by the object when it is lowered from A to B.

CHAPTER 8 Kinetic Particle Model of Matter

> **PHYSICS WATCH**
>
> Scan this page to watch a clip on the three states of water.

A geyser shooting out steam and hot water, a mountain covered in snow and a river flowing into the ocean—these are part of our natural world. Since long ago, people have been curious about the natural materials around them. They tried to classify these materials to understand their properties. The ancient Indians classified matter into five basic elements—earth, water, fire, air and empty space. The ancient Greeks believed there were four basic elements—earth, water, fire and air. Today, most people are familiar with the three states of matter.

> **QUESTIONS**
>
> - What are the three states of matter?
> - Look at the photo. Identify examples of matter in the different states.
> - What properties did you use to classify these examples?

8.1 The States of Matter

In this section, you will learn the following:

- Know the properties of solids, liquids and gases.
- Know the terms for the changes in state between solids, liquids and gases.

What are the properties of the three states of matter?

All matter can exist in *three states* — solid, liquid and gas. Water is an example of matter. Figure 8.1 shows the three different states of water.

Gas
Steam, the gaseous state of water, is invisible to the naked eye. The mist we see when water boils is actually tiny water droplets formed by steam that has condensed in the cool air.

Properties

- No fixed shape or volume
- Low density
- Compressible
- Can flow and take the shape and volume of the container

Liquid
Water in the liquid state is found in water bodies such as oceans and rivers. Only 1% of the Earth's water is suitable for drinking.

Properties

- Fixed volume but no fixed shape
- High density
- Incompressible
- Can flow and take the shape of the container

Solid
Ice, the solid state of water, exists in many forms, such as snow, glaciers, icebergs and ice cubes.

Properties

- Fixed shape and volume
- High density
- Incompressible
- Cannot flow

Figure 8.1 *Water exists in three states with different properties.*

From Figure 8.1, we can see that the properties of water depend on the state it is in. What happens in each state of water? How does water change from one state to another?

HELPFUL NOTES

Matter in the solid state is usually more dense than in the liquid state. Water is an exception. Ice is less dense than water.

WORD ALERT

Compressible: can decrease in size

Incompressible: cannot decrease in size

QUICK CHECK

The density of oxygen gas is 0.000 14 g/cm^3. The density of liquid oxygen would be greater than this.

True or false?

HELPFUL NOTES

Changing state is a physical change as no new substances are formed.

LINK

How is evaporation related to boiling? Find out more in Chapter 9.

How does matter change from one state to another?

The state of matter depends on the temperature and the pressure the matter is under. Changing the temperature of matter can change it from one state into another.

When a solid is heated, it **melts** into a liquid at its **melting point**. A liquid that is heated will **boil** and become a gas at its **boiling point**. The red arrows in Figure 8.2 show how ice melts into water and boils into steam.

When a gas is cooled to its boiling point, it will **condense** into a liquid. A liquid will **freeze/solidify** into a solid when cooled to its melting point. The blue arrows in Figure 8.2 show how steam condenses into water and freezes/solidifies into ice.

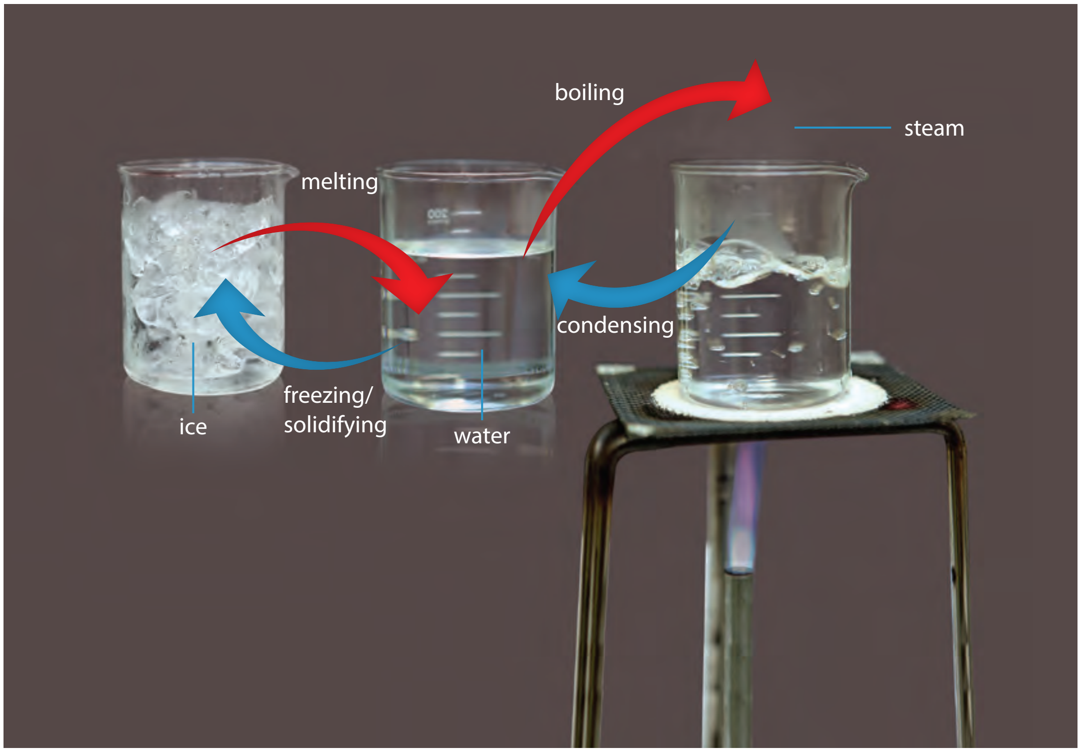


Figure 8.2 *The changes of state between solid, liquid and gas*

Let's Practise 8.1

1 Use the properties of the objects learnt in page 113 explain why
   (a) a gold ring is a solid;
   (b) milk is a liquid;
   (c) air is a gas.
2 **(a)** Explain what is meant by melting point.
   (b) Explain what is meant by condensation.
3 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

Exercise 8A, pp. XX–XX

8.2 The Particle Model

In this section, you will learn the following:

- Describe the particle structure of solids, liquids and gases, and represent these states using simple particle diagrams.
- **S** Know that the forces and distances between particles and the motion of the particles affects the properties of solids, liquids and gases.
- Describe the relationship between the motion of particles and temperature, including the lowest possible temperature (–273°C), known as absolute zero, where the particles have least kinetic energy.
- Know that the random motion of microscopic particles in a suspension is evidence for the *kinetic particle model of matter*.
- Describe and explain *Brownian motion*.
- **S** Know that microscopic particles may be moved by collisions with light, fast-moving molecules and correctly use the terms atoms, molecules and particles.

What is the kinetic particle model of solids, liquids and gases?

All matter is made up of tiny particles called atoms or molecules. Most atoms join together to make molecules. A water molecule is formed from two hydrogen atoms and one oxygen atom (Figure 8.3).

The **kinetic particle model of matter** states that the tiny particles that make up matter are always in continuous random motion. This model is used to help us understand the properties of each state of matter (Figure 8.4).

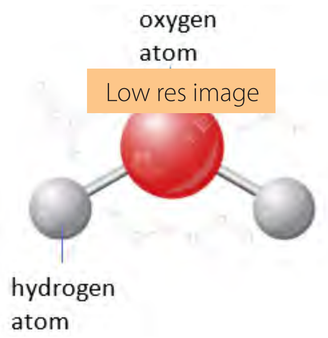
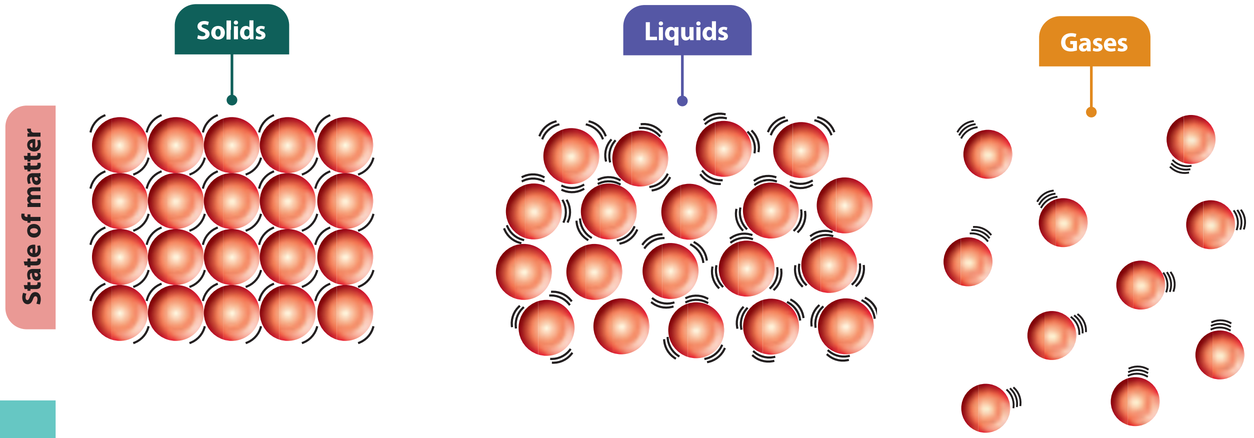


Figure 8.3 *A model of a water molecule*



Particle arrangement and movement

Solids:
- Particles are closely packed together.
- Usually in a regular pattern
- Large number of particles per unit volume
- Particles vibrate about a fixed position.

Liquids:
- Particles are slightly further apart than in solids.
- Randomly arranged
- Slightly smaller number of particles per unit volume
- Particles are free to move within the liquid.

Gases:
- Particles are far apart from one another.
- Randomly arranged
- Small number of particles per unit volume
- Particles move randomly at high speeds.

Figure 8.4 *Kinetic particle model of the three states of matter*

WORD ALERT

Random: without a pattern, cannot be predicted

How does the kinetic particle model explain the properties of solids, liquids and gases?

SOLIDS

Distance

The distance between the particles is small, so solids have a high density and are incompressible.

Force

As they are close together, the particles in solids have strong attractive forces between them. That is why solids have a fixed volume and a fixed shape.

The strong attractive forces hold the particles in fixed positions. That is why solids cannot flow.

LIQUIDS

Distance

The distance between the particles in liquids is slightly greater than in solids. That is why liquids are slightly less dense but are still incompressible and have a fixed volume.

Force

As the particles are slightly further apart, the attractive forces are not as strong as the particles in solids. The particles in liquids can move around freely. That is why liquids can flow. They do not have a fixed shape but take the shape of their container.

GASES

Distance

The distance between the particles in gases is much greater. That is why gases have low density and are compressible.

Force

As the particles are far apart, there is very little attractive force between them. That is why gases have no fixed volume or shape.

The particles move around at high speed, so gases can flow and fill the space they are put into.

close together | **distance between particles** | far apart

strong | **force of attraction between particles** | weak

Figure 8.5 *The forces and distances between particles affects the properties of solids, liquids and gases.*

PHYSICS WATCH

Scan this page to watch a clip on the kinetic models of solids, liquids and gases.

What happens to the particles when temperature increases?

When an object is heated, the temperature of the object increases. The average kinetic energy of the particles in the object increases and the particles move or vibrate faster.

When an object is cooled, the temperature of the object decreases. The average kinetic energy of the particles in the object decreases and the particles move more slowly.

The lowest temperature where the particles have the least kinetic energy occurs at **–273°C**. This temperature is also known as **absolute zero.**

What evidence is there to support the kinetic particle model of matter?

The tiny particles that make up matter cannot be seen with the naked eye. Is there evidence to show that these tiny particles are in continuous random motion?

Robert Brown was a botanist who first observed the continuous, random motion of pollen grains suspended in water. He did not know why the pollen grains were moving (Figure 8.6). Many years later, it was found that the random motion of the pollen grains was due to the motion of the water molecules. This constant random motion of the pollen grains in water was named Brownian motion.

Brownian motion refers to the *random movement* of microscopic particles in a fluid due to the collisions by the molecules of the fluid. We can only see microscopic particles under the microscope as the molecules are too small to be seen. Examples of microscopic particles are pollen grains and smoke particles.

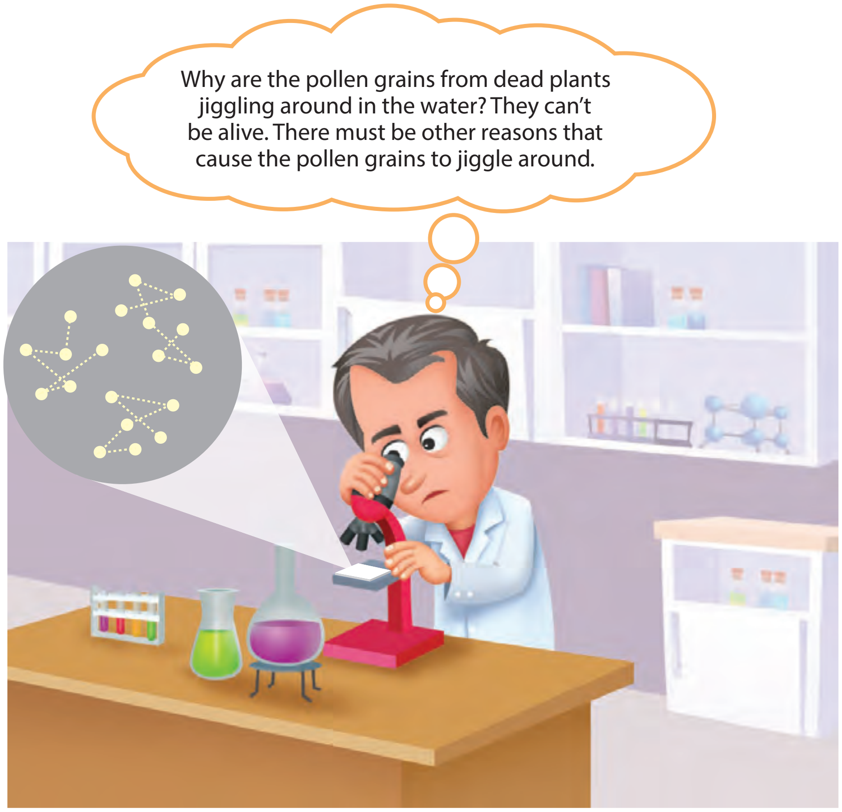


Figure 8.6 *The discovery of the constant random motion of particles by Robert Brown*

Brownian motion is also displayed by smoke particles in air (Let's Investigate 8A).

HELPFUL NOTES

Brownian motion occurs only in fluids. A fluid is any substance that has the ability to flow because the particles can move freely (e.g. liquids and gases).

PHYSICS WATCH

Scan this page to explore Brownian motion.

ENRICHMENT INFO

Tea Brewing

Have you ever observed a cup of hot water changing colour when we place a tea bag in? The spreading of the golden-brown colour of the tea is an example of Brownian motion.

The temperature of the water is important to how fast the tea spreads. The higher the temperature of the water, the faster the spreading of the tea.

Let's Investigate 8A

Objective
To study Brownian motion of smoke particles

Materials
Microscope, torchlight, glass cell containing smoke

Procedure

1 Set up the apparatus as shown in Figure 8.7.

2 Seal a glass cell containing some smoke and place it under the microscope.

3 Focus the microscope such that the smoke particles in the glass cell appear as bright dots. The smoke particles appear as bright dots because they scatter the light that shines on them.

4 Observe the motion of the smoke particles (Figure 8.8).

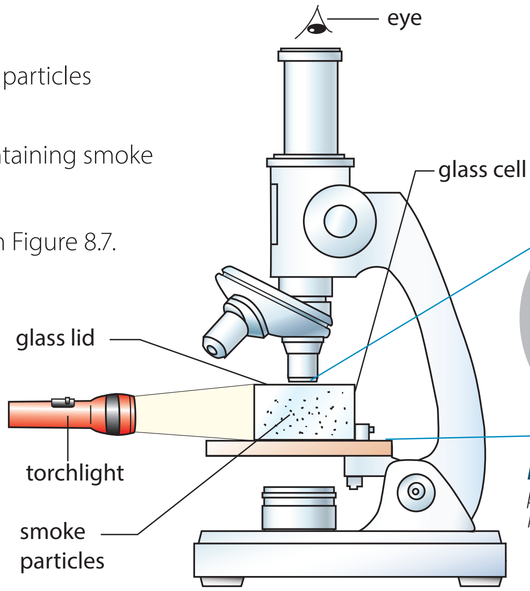


Figure 8.7 *Experimental set-up to observe Brownian motion*

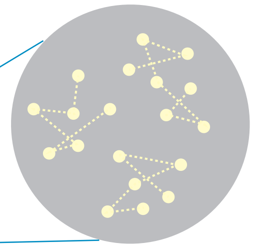


Figure 8.8 *Smoke particles moving in a random manner*

Observations

1 The smoke particles moved in a random manner.

2 The larger the particles, the less vigorous the motion.

Discussion and conclusion
The smoke particles moved randomly because air molecules were colliding with them randomly. Air molecules are too small to be seen under the microscope. This random motion of smoke particles in air is an example of Brownian motion.

LINK PWB

Practical 8, pp. xx–xx

WORD ALERT A-Z

Vigorous: moving with a great force

QUICK CHECK

Brownian motion occurs in solids.

True or false?

S How does Brownian motion occur?

Air consists mainly of nitrogen molecules, N_2, and oxygen molecules, O_2. These molecules are too small to be seen under the microscope. A smoke particle is a solid lump of many carbon atoms. When light is shone on a mixture of smoke particles in air, the smoke particles can be seen as tiny specks of reflected light. How can a larger, more massive particle be affected by smaller lighter molecules in the air?

There are millions of molecules in the air moving at high speeds in all directions. This means that there are many collisions on each smoke particle happening all the time. The smoke particle is constantly pushed one way and then another. As we cannot see the molecules, the smoke particles appear to be constantly moving small distances in a random path.

Let's Practise 8.2

1 Describe the particle structure and arrangement of ice, water and steam.

2 S Using the kinetic particle model of matter, explain
(a) why a liquid takes the shape of its container;
(b) why the density of a gas is less than that of a solid;
(c) why the smell of the perfume spreads throughout the room.

3 **(a)** Explain what Brownian motion is.
(b) How would Brownian motion change if the temperature is increased?

4 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

Exercise 8B, pp. XX–XX

8.3 Gases and the Absolute Scale of Temperature

In this section, you will learn the following:

- Describe the pressure and the changes in pressure of a gas.
- S Describe the pressure and changes in pressure of a gas as *force per unit area*.
- Describe qualitatively, the effect on the pressure of a fixed mass of gas with changing temperature at constant volume and changing volume at constant temperature.
- S Recall and use the equation pV = constant for a fixed mass of gas at constant temperature, including a graphical representation of this relationship.
- Convert temperatures between kelvin and degrees Celsius.
- Recall and use the relationship T (in K) = θ (in °C) + 273.

How do gases exert a pressure?

The kinetic particle model also explains how a gas exerts a pressure. Figure 8.9 is a diagram of gas particles in a container.

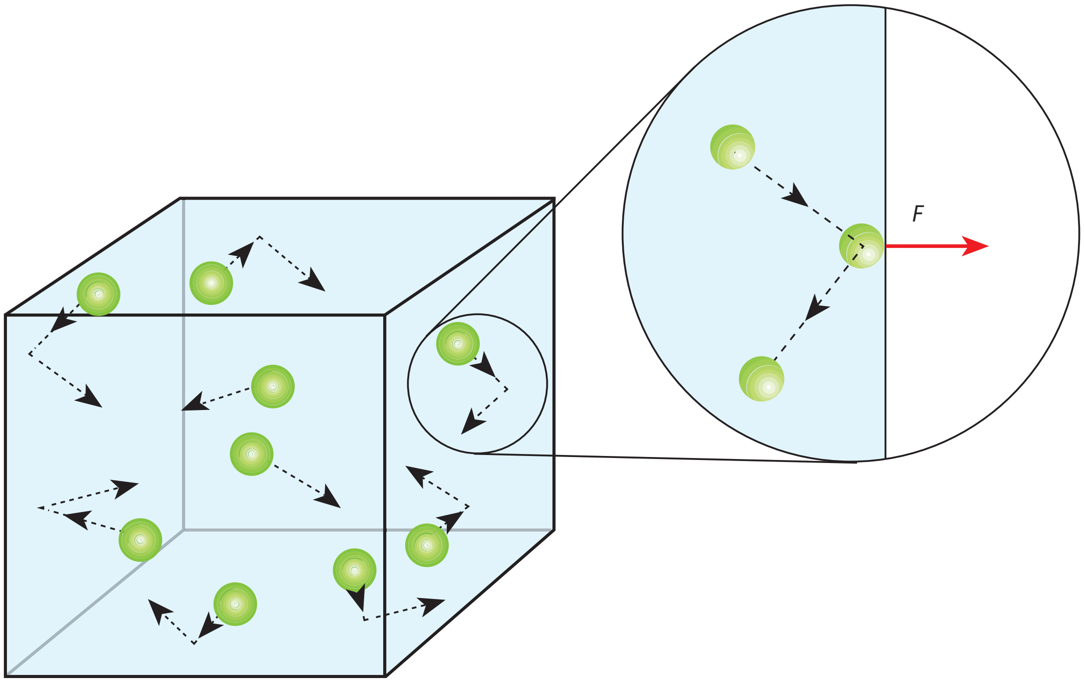


Figure 8.9 *The constant collision of air particles on the walls of the container exerts a pressure on the container.*

The gas particles are moving randomly in all directions. They collide with one another and with the walls of the container. The pressure on the container is caused by the *constant collisions* of many particles with its walls.

S When the particles collide with the walls of the container, they exert a *force* on the wall (Figure 8.9). The force from one collision is small but as there are many particles colliding all of the time, the force exerted is large.

From Chapter 7, we learnt that pressure is force per unit area. Hence, the force exerted by the collisions of gas particles on the container gives rise to the pressure on the container.

LINK

Recall what you have learnt about pressure in Chapter 7.

What do you think will happen to the pressure of the gas in the container if the temperature is increased but the volume stays the same?

How does the pressure of a gas vary with its temperature?

When the temperature of the air in the tyres increases, the pressure of the air in the tyres also increases. Can the kinetic particle model be used to explain this relationship? Let us consider what happens to a fixed mass of air inside a tyre of fixed volume (Figure 8.10).

1. When the car is moving, the tyres get heated. This causes the temperature of the air in the tyres to rise.
2. The air particles collide with the inner surface of the tyres more vigorously and more frequently.
3. Using the kinetic particle model of matter, a rise in the temperature of the air causes an increase in the average speed of the air particles.
4. S The average force per collision between the air particles and the wall of the tyre increases, and since the volume of the tyres is fixed, the pressure inside the tyres increases.

Figure 8.10 *Heat generated in an overinflated car tyre after a long journey could burst the tyre because of increased pressure.*

For a fixed volume and mass of gas, increasing its temperature results in an increase in the speeds of the gas particles (Figure 8.11). This increases the rate at which the particles collide with the walls of the container.

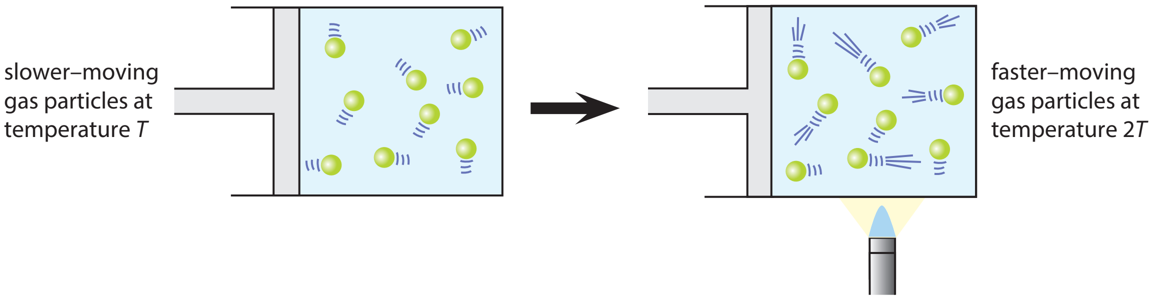


Figure 8.11 *The speed of the gas particles increases as temperature increases.*

From Figure 8.12, we can see that *the gas pressure of a gas at fixed volume and mass increases with temperature.*

What do you think will happen to the pressure of the gas in the container if the volume is increased but the temperature is constant?

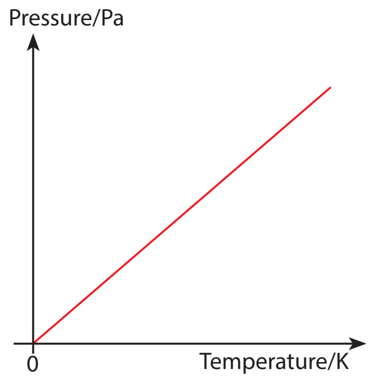


Figure 8.12 *Pressure–temperature graph of a gas at constant volume*

ENRICHMENT *ACTIVITY*

Make a bottle crumple using air pressure!

Pour very hot water into a plastic bottle until it is half full.

(Note: Be careful not to burn yourself with the water!)

Swirl the water around in the bottle for about a minute. Pour the water out and quickly screw the cap tightly onto the bottle.

Pour cold water over the sides of the bottle. The bottle will suddenly crumple.

Can you use the kinetic particle model of matter to explain why the bottle crumples?

PHYSICS WATCH

Scan this page to explore the pressure–temperature relationship of a gas.

How does the pressure of a gas vary with its volume?

Have you noticed how bubbles in a fish tank increase in size as they rise from the bottom of the tank to the top? Do you know why this happens? Using the apparatus in Figure 8.13, let us study the relationship between the pressure and the volume of a gas when its temperature remains constant.

The gas to be studied is trapped in the syringe. Pressure is measured by the pressure gauge, and volume is read from the syringe's scale when the gas is at the same temperature as its surroundings. When the piston is pushed inwards, the pressure registered by the pressure gauge increases. Why?

1. Using the kinetic particle model of matter, a decrease in the volume of gas means that the number of particles per unit volume increases.
2. Therefore, the gas particles collide more frequently with the inner surface of the syringe and this results in a greater pressure as shown on the pressure gauge.

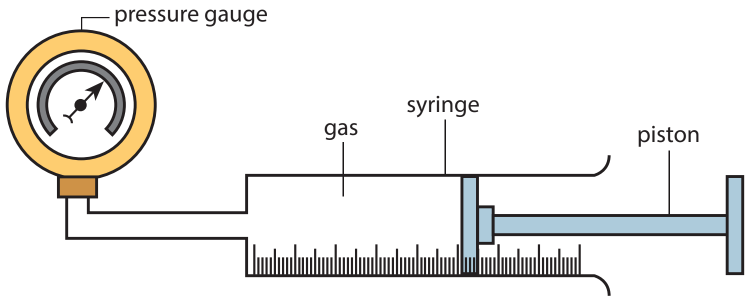
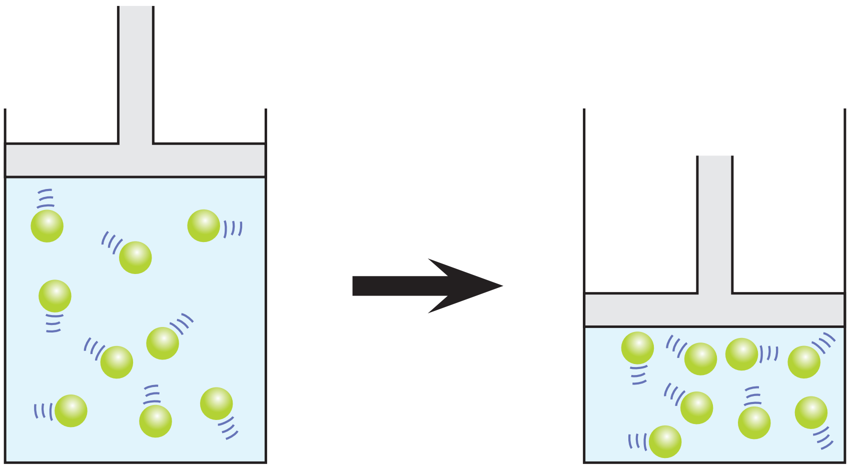


Figure 8.13 *Experimental set-up to study the volume and pressure of a gas at constant temperature*

For a fixed mass of gas at constant temperature, a decrease in volume results in particles having less space to move in (Figure 8.14). Hence, this increases the rate at which particles collide with the walls of the container.



▲ Gas particles at volume 2*V*

▲ Gas particles at volume *V*

Figure 8.14 *The amount of space that the particles can move in decreases as volume decreases.*

The gas pressure of a fixed mass of gas at constant temperature increases when the volume decreases.

QUICK CHECK

When the volume of the gas in Figure 8.14 increases, the pressure decreases.

True or false?

From Figure 8.14, when the volume of the gas is halved, the pressure of the gas is doubled. The decrease in the volume resulting in a proportional increase in pressure is known as **inverse proportionality**. Figure 8.15 is a graph showing the inverse proportion relationship between pressure and volume.

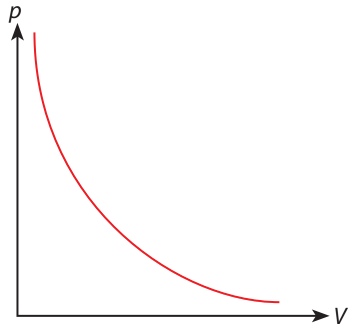
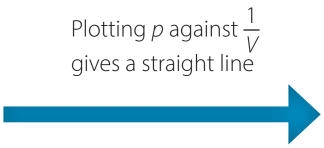


Figure 8.15 Pressure-volume graph of a gas at constant temperature



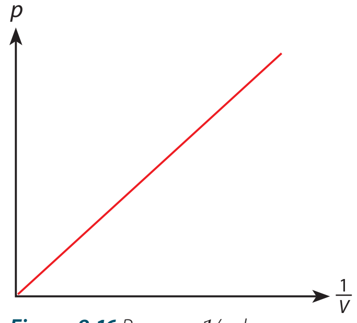


Figure 8.16 Pressure-1/volume graph of a gas at constant temperature

For an inverse proportionality,

$p \propto \frac{1}{V}$ or $p = \frac{k}{V}$ where p = pressure

k = proportionality constant

V = volume

Rearranging the equation $p = \frac{k}{V}$, we will get $\boldsymbol{pV = k}$ or $\boldsymbol{pV}$ **= constant**

If we have a gas at pressure p_1, volume V_1, and we change the pressure and the volume of the gas to p_2 and V_2 at constant temperature, we can write the equations like this:

Initial $p_1V_1 = k$

Final $p_2V_2 = k$

As k is the same for both equations, we can combine the two equations.

$\therefore \boldsymbol{p_1V_1 = p_2V_2}$

Using the above equation, we can find the change in the pressure and/or the volume of a gas at constant temperature.

Worked Example 8A

A gas cylinder contains 600 ml of carbon dioxide at a pressure of 2×10^7 Pa. Assuming that the temperature of the gas does not change, calculate the volume of the gas at atmospheric pressure, 1×10^5 Pa.

Solution

Given: $p_1 = 2 \times 10^7$ Pa

$p_2 = 1 \times 10^5$ Pa

$V_1 = 600$ ml

$p_1V_1 = p_2V_2$

$2 \times 10^7 \times 600 = 1 \times 10^5 \times V_2$

$V_2 = 1.2 \times 10^5$ ml

HELPFUL NOTES

$\propto$ is a symbol used to represent that a physical quantity is proportional to another physical quantity.

ENRICHMENT THINK

A balloon is tied to the top of a jar. A vacuum pump then pumps air out of the jar and the balloon expands (Figure 8.17).

Figure 8.17 A balloon in a jar expands when air in the jar is removed.

1 Explain why the balloon expands when air is removed from the jar.
2 Describe what will happen when air is let back into the jar.
3 Which relationship is this demonstrating?

How did absolute zero lead to a new temperature scale?

Most countries use degrees Celsius, °C, to measure temperature. On the Celsius scale, 0°C is the temperature of pure melting ice and 100°C is the temperature of pure boiling water at standard pressure. The scale between these two temperatures is divided into 100 ticks with equal spacing, where the difference between each tick equals to 1°C change (Figure 8.18).

Temperature can also be measured using kelvin, K , which is the SI unit for temperature. The **Kelvin scale** of temperature has absolute zero as 0 kelvin, or 0K. One degree change on the Kelvin scale is the same as one degree change on the Celsius scale. This makes it easy to convert from one temperature scale to another (Figure 8.19).

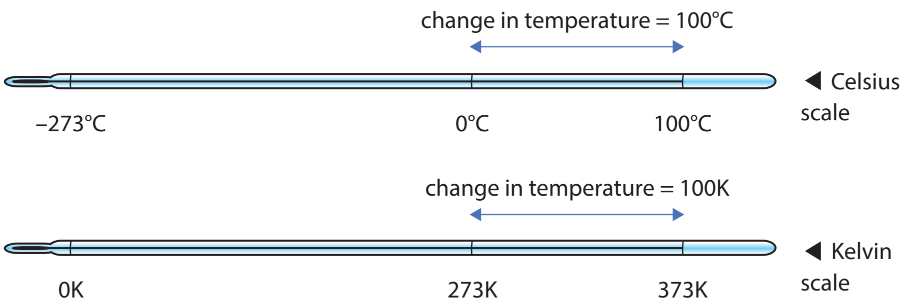


Figure 8.19 Celsius scale and Kelvin scale

Figure 8.18 A glass thermometer with a Celsius scale

From Figure 8.19, can you see how to convert a temperature (θ) measured in °C into a temperature (T) in K?

T (in K) = θ (in °C) + 273

Worked Example 8B

The temperature in a room is 20°C. What is the temperature of the room in kelvin?

Solution

T (in kelvin) = θ (in °C) + 273

$T = 20 + 273$

$= 293\text{K}$

Let's Practise 8.3

1 Using the kinetic particle model of matter, explain
 (a) how the air particles in a container exert pressure on the walls of the container;
 (b) why the pressure of the air increases as the temperature increases.

2 (a) Describe how the pressure of a gas changes with volume when the temperature of the gas is constant.
 (b) S Give the equation for the relationship between pressure and volume of a gas when the temperature of the gas is constant.

3 Describe one similarity and one difference between the Celsius and Kelvin temperatures scales.

4 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK

Recall that absolute zero = –273°C in Section 8.2 of this chapter.

HELPFUL NOTES

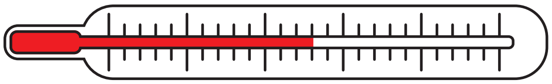
T is usually used to refer to temperature in kelvin and θ is usually used to refer to temperature in degrees Celsius.

LINK TWB

Exercises 8C–8D, pp. XX–XX

Exercise 8E Let's Practise, p. XX

Let's Map It



KINETIC PARTICLE MODEL OF MATTER

is proven by

Brownian motion

states that

Matter is made of tiny particles that are in continuous random motion.

where

- Particles have greater kinetic energy at higher temperature
- Particles have least energy at absolute zero

which

- 0K in kelvin
- −273°C in degree Celsius

converted using the equation
T (in K) = θ (in °C) + 273

which exist in three states known as

Solids

- Particles are closely packed
- Arranged in a regular pattern
- Large number of particles per unit volume
- Particles vibrate about fixed positions
- S Attractive forces between particles are very strong

melting

freezing/ solidifying

Liquids

- Particles are slightly further apart
- Randomly arranged
- Slightly smaller number of particles per unit volume
- Particles can move freely within the liquid
- S Attractive forces between particles are moderately strong

boiling

condensing

Gases

- Particles are far apart
- Randomly arranged
- Small number of particles per unit volume
- Particles move randomly at high speeds
- S Attractive forces between particles are negligible

where

Gas pressure is due to the collision of gas particles with the walls of the container

which increases with

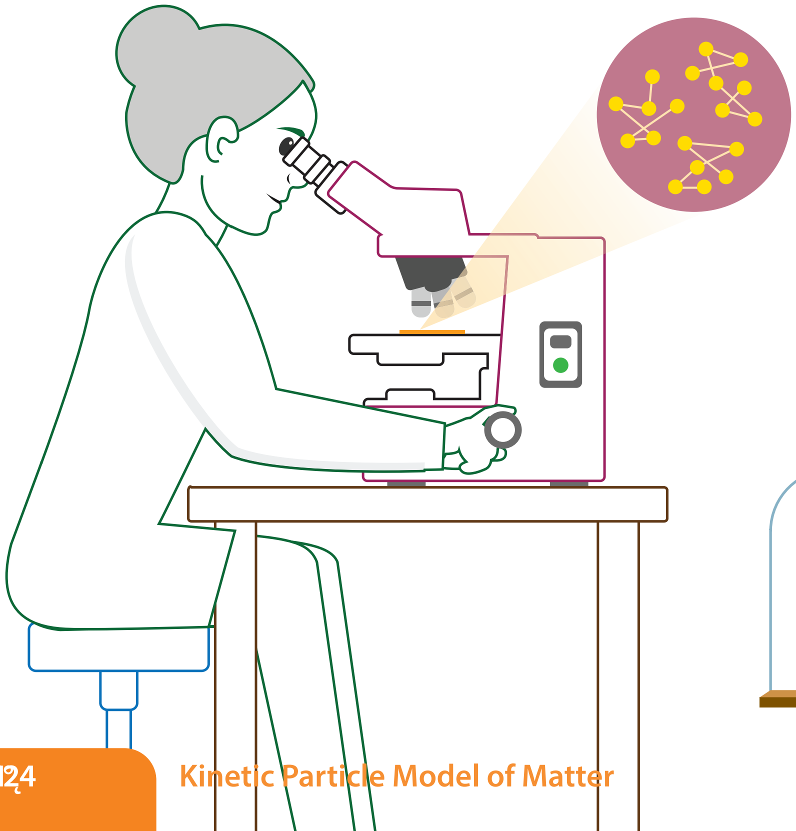
Temperature at constant volume

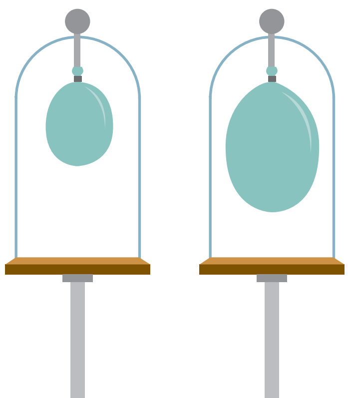
which decreases with

Volume at constant temperature

its equation is given by

S $pV = k$





Let's Review

Section A: Multiple-choice Questions

1 Which states of matter are fluids?
- **A** Liquids and gases only
- **B** Solids and liquids only
- **C** Solids, liquids and gases
- **D** Solids and gases only

2 Which of the following statements about Brownian motion is correct?
- **A** It applies to gases only.
- **B** The motion of smoke particles in air is due to the smoke particles colliding with one another.
- **C** The smoke particles in air can be observed to dance in a regular pattern.
- **D** The smoke particles in air will slow down when the air temperature is decreased.

3 A gas is heated in a sealed container of constant volume. Which of the following will **not** increase?
- **A** The average speed of the gas particles
- **B** The number of particles per unit volume
- **C** The pressure of the gas
- **D** The temperature of the gas

4 Which statement is **not** correct?
- **A** 300K is equal to 27°C.
- **B** –273°C is the coldest temperature possible.
- **C** Ice melts at 273K.
- **D** The lowest temperature on the Celsius scale is 0°C.

5 S Which statement is **not** needed to explain why a gas exerts a pressure on the walls of its container?
- **A** Gas particles cause a force on the walls of the container as they collide.
- **B** Gas particles collide with one another.
- **C** Gas particles collide with the walls of the container.
- **D** Pressure, $p = \frac{\text{force}}{\text{area}}$

Section B: Short-answer and Structured Questions

1 **(a)** What is seen moving in a Brownian motion experiment?
(b) Why is a microscope necessary to observe Brownian motion?
(c) Explain how Brownian motion provides evidence for the kinetic particle model of matter.

2 Figure 8.20 is a diagram of a bicycle pump.

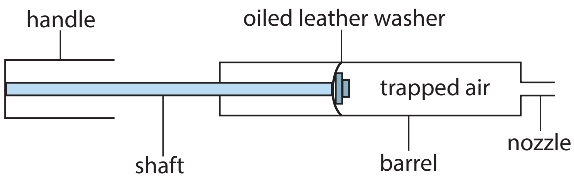


Figure 8.20

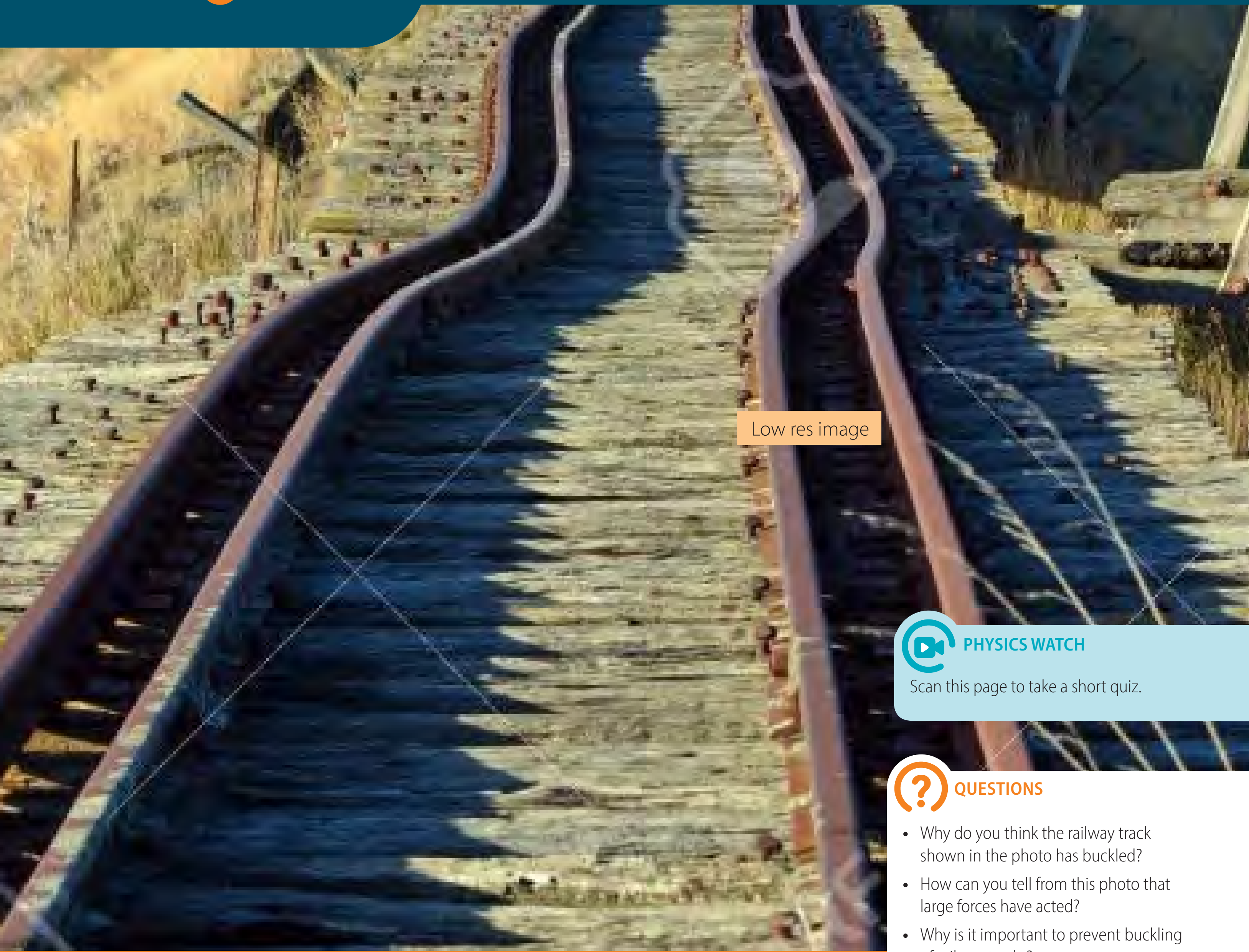
When the nozzle of the pump is blocked and the handle is slowly pushed to the right, the temperature of the air in the barrel remains constant, while the pressure of the air rises.

(a) Using the motion of the air particles, explain how the trapped air creates pressure on the washer. Assume that there is no leakage of air past the washer.
(b) Why does the pressure of the air in the barrel increase when the handle is slowly pushed in?

3 S A sample of gas at atmospheric pressure of 1×10^5 Pa has a volume of 100 cm^3.
(a) Determine the pressure of the gas when its volume is halved.
(b) Determine the pressure of the gas if the volume is reduced to 85 cm^3.
(c) Determine the volume if the pressure is reduced to 6×10^4 Pa.

CHAPTER 9

Thermal Properties and Temperature



PHYSICS WATCH

Scan this page to take a short quiz.

QUESTIONS

- Why do you think the railway track shown in the photo has buckled?
- How can you tell from this photo that large forces have acted?
- Why is it important to prevent buckling of railway tracks?
- Can you think of ways to prevent this from happening?

The railway track shown in the photo was originally built to be a straight-line track. However, tracks such as this often buckle or bend during hot weather. Engineers need to apply their understanding of thermal properties of matter to reduce the problem of track buckling.

9.1 Thermal Expansion

In this section, you will learn the following:

- Describe qualitatively the thermal expansion of solids, liquids and gases at constant pressure.
- Describe some of the everyday applications and consequences of thermal expansion.
- S Explain, in terms of the motion and arrangement of particles, the relative order of magnitudes of the expansion of solids, liquids and gases as their temperatures rise.

What happens when materials are heated?

Solids, liquids and gases increase in volume or expand when heated. The greater the temperature rise, the greater the expansion. When cooled, the volume will decrease, i.e., it will contract.

The amount that solids expand is so small that it cannot be detected visually. In Figure 9.1 the metal ball just passes through the metal ring at room temperature. After heating, the metal ball has expanded. It is now too big to pass through the metal ring.

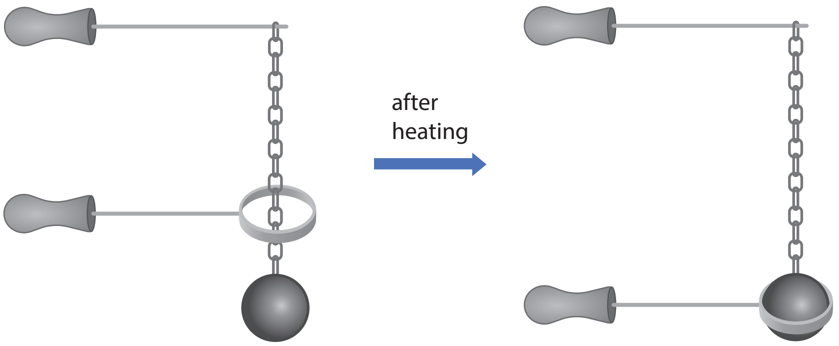


Figure 9.1 *Expansion of a metal*

PHYSICS WATCH

Scan this page to watch an experiment on thermal expansion and contraction of a solid.

Liquids expand more than solids for the same temperature rise. This is the principle behind liquid-in-glass thermometers (Figure 9.2).

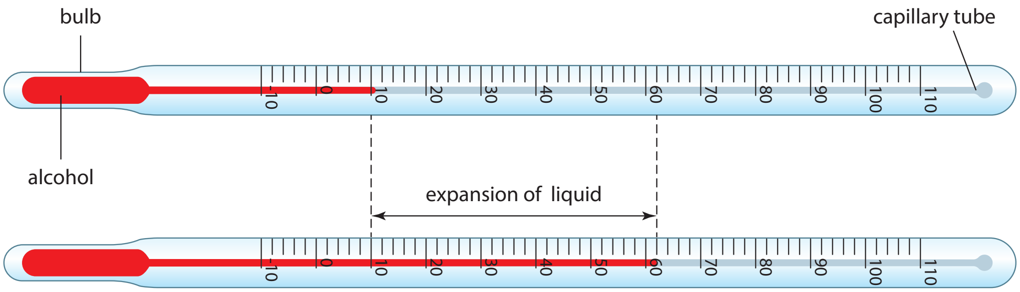


Figure 9.2 *Expansion of a liquid in a thermometer*

When the bulb of alcohol is heated, you can see the liquid expanding along the thin capillary tube inside.

Gases expand much more than liquids. The warmth of your hands is enough to make air expand by a large amount. As shown in Figure 9.3, the air in the test tube expands and bubbles of air are seen escaping from the tube.

Figure 9.3 *Expansion of air*

LINK

Recall what you have learnt in Chapter 8 about the effect of particles in matter when it is heated.

QUICK CHECK

Solids expand because their particles become bigger.

True or false?

Why do solids, liquids and gases expand by different amounts?

Heating materials gives the particles more kinetic energy. In solids, the particles vibrate more vigorously. Strong forces between them results in a small expansion.

In liquids, the particles move around faster. The forces between the particles are weaker as compared to solids, so the expansion is greater.

Gas particles move about the fastest as compared to solid and liquid particles. Gases have the greatest expansion because there is little force between the particles.

When materials are heated, the particles themselves do not expand, but the volume that they occupy does (Figure 9.4).

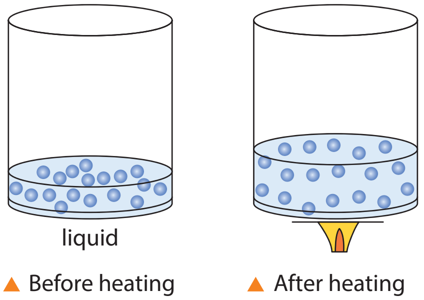


Figure 9.4 *The volume of a liquid expands when heated, while the size of the particles remains the same.*

What are the applications and consequences of expansion?

As shown in the chapter opener, if there is no space to expand, large forces may act. Engineers must take expansion into account when designing structures.

Railway lines

Some railway lines have expansion gaps to allow for expansion when the lines get hot. (Figure 9.5)

Modern railway lines do not have gaps. This is to allow the trains to move more smoothly. The lines are designed to fit tightly on a hot day. On cold days, the lines contract, but they are still held in place by supporting structures underneath.

Figure 9.5 *Expansion gaps in a length of rail*

Bridges

Bridges also expand and contract with changes in temperature. Figure 9.6 shows an expansion gap at one end of a concrete bridge. Another way of allowing for expansion is to put one end of the bridge on rollers (Figure 9.7).

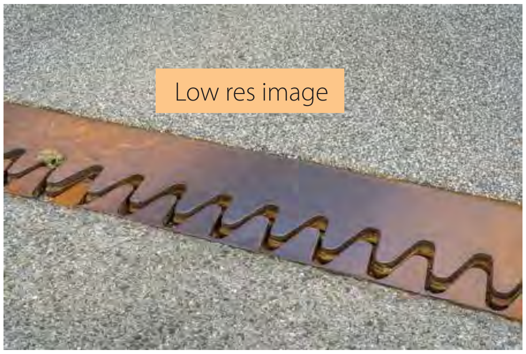


Figure 9.6 *Expansion gaps in a bridge roadway*

Figure 9.7 *Rollers supporting one end of a bridge*

Shrink fitting

Expansion can be used to fix two metal parts together using shrink fitting.

An example is fitting a metal axle into a metal train wheel (Figure 9.8). The metal axle is first made too large for the hole in the metal train wheel. Then, the axle is cooled to shrink so it will fit into the wheel. When the axle warms up and expands, the two metals are firmly held together.

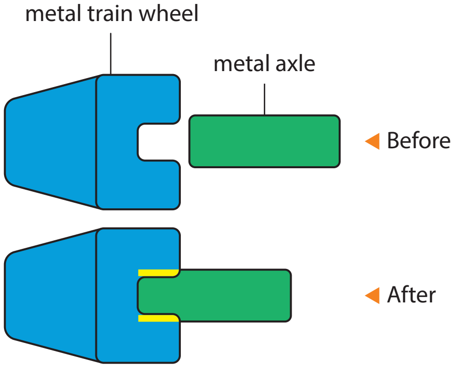


Figure 9.8 *Shrink fitting two metal parts together using thermal expansion*

Let's Practise 9.1

1. What evidence is there that the forces caused by expansion are large?
2. Explain why overhead telephone wires hang more loosely on a hot day.
3. S Explain using the kinetic particle model of matter why solids contract when they are cooled.
4. **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

TWB LINK

Exercise 9A, pp. XX–XX

9.2 Specific Heat Capacity

In this section, you will learn the following:

- Know that a rise in the temperature of an object increases its internal energy.
- S Describe an increase in temperature in terms of an increase in the average kinetic energies of all of the particles in the object.
- S Recall and use the equation $c = \dfrac{\Delta E}{m\Delta\theta}$.
- S Describe experiments to measure the specific heat capacity of a solid and a liquid.

What is internal energy?

The **internal energy** of a substance is the *total energy of all of its particles*. When the temperature of a substance is above 0 Kelvin, there is internal energy. In Figure 9.9, thermal energy is transferred from the flame of the Bunsen burner to the water. The internal energy of the water increases because the particles have gained kinetic energy. The water becomes hotter. Therefore, the higher the temperature, the greater the internal energy.

The higher the temperature of a substance (measured in °C or K), the greater the internal energy of the substance (measured in J).

The thermal energy from the Bunsen burner causes the water molecules to move faster. Molecules that move faster have greater kinetic energy. The internal energy of the water has increased because the total energy of all of the molecules has increased.

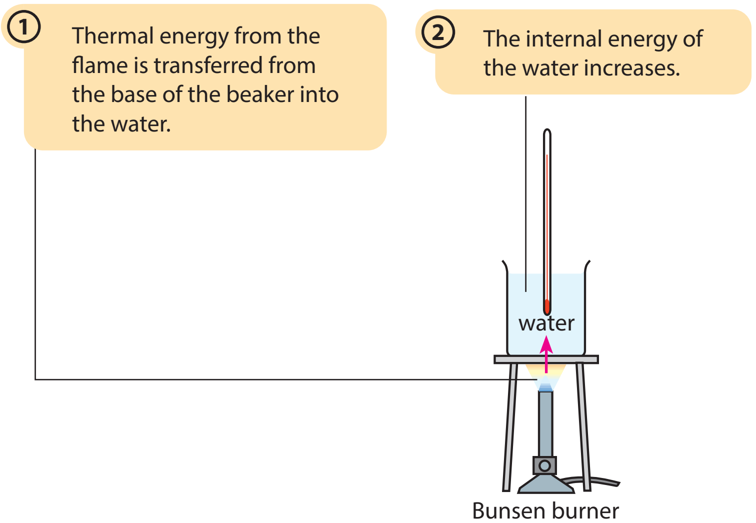


Figure 9.9 *Heating a beaker of water*

S Temperature is a measure of the average kinetic energy of the particles. The higher the temperature, the greater the internal energy.

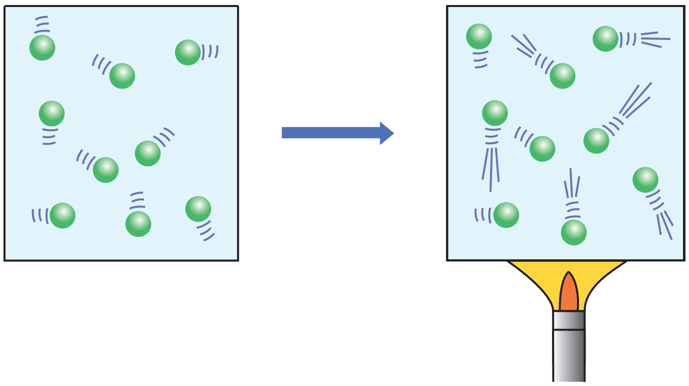


Figure 9.10 *The molecules have higher kinetic energy when heated up.*

What is specific heat capacity?

It is useful to be able to calculate how much energy is needed to heat things. What do you think this depends on?

When you boil water for a drink, the more water you heat, the longer it takes to boil. This shows that

- the thermal energy needed depends on the mass of water being heated.

If the water is colder to begin with, it takes longer to boil. This shows that

- the thermal energy needed depends on the temperature change.

Water takes a lot of thermal energy to heat up compared with other substances. This is why sand on a beach heats up — and cools down — more quickly than the sea. This shows that

- the thermal energy needed depends on the material being heated.

Specific heat capacity c is defined as the amount of thermal energy required to raise the temperature of a unit mass (e.g. 1 kg) of a substance by 1°C (or 1 K).

The definition gives us the equation for specific heat capacity:

$$c = \frac{\Delta E}{m\Delta\theta}$$

where ΔE = thermal energy required (in J)

$\Delta\theta$ = temperature change (in K or °C)

m = mass of substance (in kg)

The SI unit of specific heat capacity is the **joule per kilogram per kelvin, J/(kg K)**, or the **joule per kilogram per degree Celcius, J/(kg°C)**.

The equation can be rearranged as $\Delta E = mc\Delta\theta$.

Table 9.1 shows that the specific heat capacity of water is 4200 J/(kg K). This tells us that it takes 4200 joules of energy to change the temperature of 1 kg of water by 1°C.

Table 9.1 Specific heat capacity of some common materials

Material	Lead	Mercury	Brass	Zinc	Copper	Iron	Glass	Aluminium	Methylated spirit	Seawater	Water
Specific heat capacity J/(kg K)	130	140	380	390	400	460	670	900	2400	3900	4200

QUICK CHECK

Refer to Table 9.1. It requires more energy to raise the temperature of 1 kg of sea water by 1 K than 1 kg of tap water.

True or false?

Worked Example 9A

Calculate the temperature change of 1 kg of copper when it is supplied with 4200 J of thermal energy.

Solution

Using $\Delta E = mc\Delta\theta$

$4200 = 1 \times 400 \times (\Delta\theta)$

$\Delta\theta = 10.5$ K

HELPFUL NOTES

Remember that a temperature change of 1 K is the same as a temperature change of 1°C.

How is specific heat capacity determined?

Let's Investigate 9A shows how the specific heat capacity of solid can be determined using a cylindrical block of metal. The block has a hole bored for the heater and another for the temperature sensor (Figure 9.11).

Let's Investigate 9A

Objective
To determine the specific heat capacity of a solid

Apparatus and materials
Metal block with holes drilled in for heater and temperature sensor, temperature sensor and data logger, electrical heater, d.c. power supply, ammeter, voltmeter, connecting leads, insulating felt cloth for metal block, electronic balance, stopwatch

Procedure

1 Measure and record the mass, *m*, of the solid with an electronic balance.
2 Wrap the block with felt cloth. This is to reduce heat loss to the surroundings.
3 Connect the d.c. power source to the heater and put the heater into one of the holes of the block. Place the temperature sensor into the other hole (Figure 9.11).
4 Connect the temperature sensor to the data logger. Set the data logger to record temperature.
5 Start recording the temperature. Note the initial temperature θ_1.
6 Switch on the power supply for *t* seconds.
7 After *t* seconds, switch off the heater. Continue recording the temperature for a while. Note the highest temperature θ_T reached.

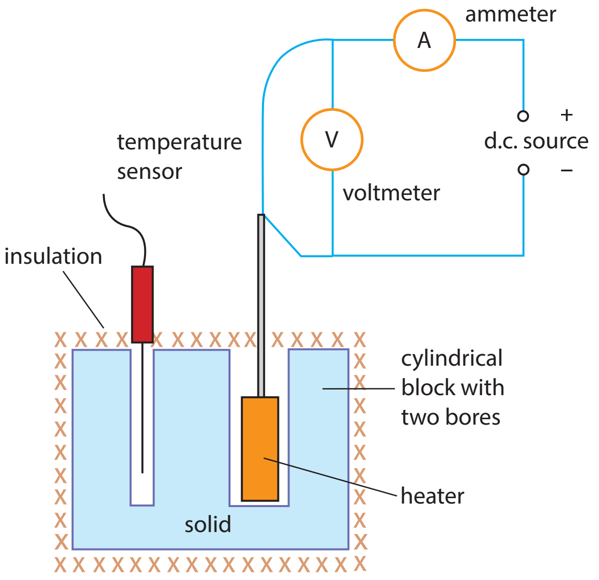


Figure 9.11

Calculation

Power *P* of heater = current *I* × voltage *V*

Since it is used for *t* seconds, the thermal energy ΔE provided by the heater = IVt

Assuming all of the thermal energy provided by the heater is absorbed by the solid block,

$\Delta E = mc\Delta\theta$

$IVt = mc\Delta\theta$

where $\Delta\theta = \theta_T - \theta_1$

Therefore, the specific heat capacity of aluminium is given by

$$c = \frac{IVt}{m\Delta\theta}$$

Note: Since we assume that no heat is lost to the surroundings in the calculation above, good insulation is important in this experiment.

LINK

Investigations 9A and 9B use the equation for electrical power, which is explained in Chapter 16.

ENRICHMENT THINK

Not all of the thermal energy from the heater will go into the solid.

1 Explain why.
2 What does this mean about the value used for ΔE in this experiment?
3 How will it affect the result of the experiment?
4 Will the value for *c* be higher or lower than the expected value?

LINK PWB

Practical 9A, pp. XX–XX

Worked Example 9B

An electric heating coil supplies 50 W of power to a metal block of 0.60 kg. In 90 s, the temperature of the block is raised from 20°C to 45°C. Calculate the specific heat capacity of the metal. State the assumption you made to arrive at your answer.

Solution

Given: Power P of heater = 50 W

Time taken t = 90 s

Mass m of block = 0.60 kg

Change in temperature $\Delta\theta$ = 45°C – 20°C

= 25°C

Thermal energy supplied by heater = $P \times t$ = 50 W × 90 s = 4500 J

Assuming no heat is lost to the surroundings,

thermal energy supplied by the heater = thermal energy absorbed by the block

$$Pt = mc(\Delta\theta)$$

Therefore, the specific heat capacity c of the metal $= \dfrac{Pt}{m\Delta\theta}$

$$= \frac{4500\ J}{0.60\ kg \times 25}$$

= 300 J/(kg K)

Worked Example 9C

Some liquid in a copper **calorimeter** was heated using an electrical heater in order to find its specific heat capacity. The results are given below.

Mass of calorimeter	= 270 g	Time	= 360 s
Mass of liquid	= 260 g	Initial temperature	= 18°C
Potential difference	= 12.0 V	Final temperature	= 30°C
Current	= 3.4 A		

(a) Use the results to find

(i) the energy in joules supplied by the heater;

(ii) the energy in joules absorbed by the calorimeter;

(iii) the specific heat capacity of the liquid.

(b) State the assumptions that have been made in your answer to **(a)(iii)**.

Copper has a specific heat capacity of 400 J/(kg K).

Solution

(a) (i) Energy supplied by heater = IVt = 3.4 A × 12.0 V × 360 s = 14 688 J

(ii) Energy absorbed by calorimeter = $mc\Delta\theta$ = 0.27 kg × 400 J/ (kg K) × (30 – 18)°C = 1296 J

(iii) ΔE = energy supplied by heater – energy absorbed by calorimeter

= 14 688 J – 1296 J

= 13 392 J

Specific heat capacity $c = \dfrac{\Delta E}{m\Delta\theta} = \dfrac{13\,392\ \text{J}}{0.26\ \text{kg} \times (30 - 18)°\text{C}}$ = 4292 J/(kg K)

(c) The assumption is that all of the energy from the heater is absorbed by the calorimeter and water.

WORD ALERT

Calorimeter: an apparatus used to measure heat

HELPFUL NOTES

The principle of conservation of energy, covered in Chapter 6, is useful for solving problems in this chapter.

S

Let's Investigate 9B

Objective
To determine the specific heat capacity of a liquid

Materials
Polystyrene cup and polystyrene lid with holes for heater and temperature sensor, liquid e.g. water or oil, electronic balance, temperature sensor and data logger, electrical heater, d.c. power supply, ammeter, voltmeter, connecting leads, stopwatch

Procedure

1 Measure and record the mass of liquid m.
2 Pour the liquid, whose specific heat capacity c we want to determine, into the polystyrene cup.
3 Place the heater and the temperature sensor in the liquid (Figure 9.12).
4 Connect the temperature sensor to the data logger. Set the data logger to record temperature.
5 Start the recording of temperature. Note the initial temperature θ_1.
6 Switch on the power supply for t seconds.
7 After t seconds switch off the heater. Continue recording the temperature for a while. Note the highest temperature θ_2 reached.

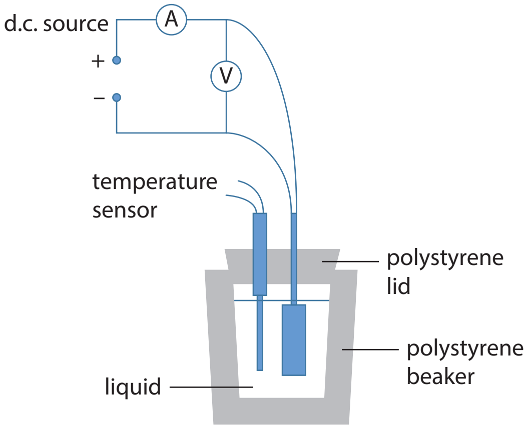


Figure 9.12

Calculation
Thermal energy supplied by heater, $\Delta E = IVt$

Thermal energy absorbed by liquid $= mc\Delta\theta = mc(\theta_2 - \theta_1)$

Assuming all the thermal energy supplied is absorbed by the liquid, (i.e. no heat loss to the surroundings),

thermal energy supplied by heater = thermal energy absorbed by liquid

$$IVt = mc(\theta_2 - \theta_1)$$

Therefore, the specific heat capacity c of the liquid is given by $c = \dfrac{IVt}{m(\theta_2 - \theta_1)}$

LINK PWB

Practical 9B, pp. XX–XX

Let's Practise 9.2

1 A beaker contains 100 cm^3 of water at 20°C. State whether the following changes would cause the internal energy of the water to increase, decrease or stay the same.
   (a) Heating the water to 40°C
   (b) Boiling the water to 100°C
   (c) Removing 50 cm^3 of water from the beaker
   (d) Adding 50 cm^3 of water at 20°C to the beaker
2 S Explain why on a hot sunny day the sand at the beach is hotter than the water in the sea.
3 S 100 g of a metal needs 1000 J to raise its temperature by 9°C. Calculate the specific heat capacity of the metal.
4 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

Exercise 9B, pp. XX–XX

9.3 Changes of State

In this section, you will learn the following:

- Describe *melting* and *boiling* in terms of energy input without a change in temperature.
- Know the melting and boiling temperatures for water at standard atmospheric pressure.
- Describe *condensation* and *solidification* in terms of particles.
- Describe *evaporation* in terms of the escape of more energetic particles from the surface of a liquid.
- Know that evaporation causes cooling of a liquid.
- S Describe the differences between boiling and evaporation.
- S Describe how temperature, surface area and air movement over a surface affect evaporation.
- S Explain the cooling of an object in contact with an evaporating liquid.

What happens to the temperature when materials change state?

Remember from Chapter 8 that melting occurs when a solid changes into a liquid upon being heated. Boiling occurs when a liquid turns into a gas upon being heated. You can find out using the apparatus shown in Figure 9.13 what happens to the temperature of a substance when it changes state.

Start with very cold crushed ice from the freezer. Heat it and record the temperature every minute until the melted ice boils.

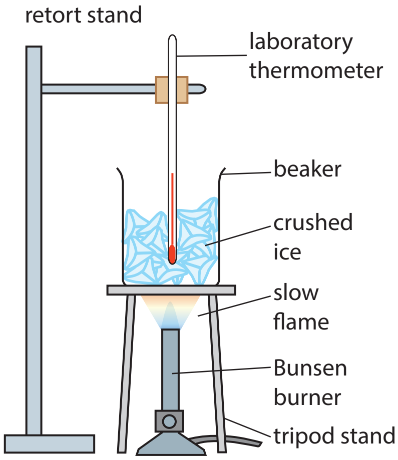


Figure 9.13 *Heating ice*

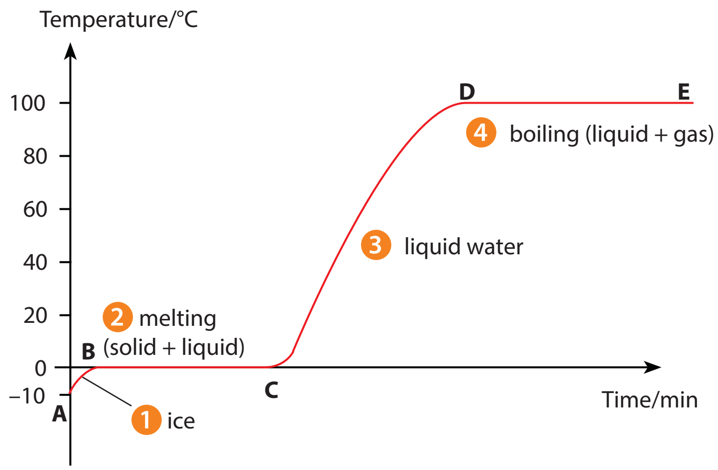


Figure 9.14 *Graph of heating curve of water*

Figure 9.14 shows a graph of temperature against time.

From A to B, the graph is a curve. The temperature of the ice rises from –10°C to 0°C. There is a change of temperature. The thermal energy is being taken in to increase the temperature.

From B to C, the graph is a horizontal straight line. The temperature remains constant at 0°C. Thermal energy continues to be supplied from the Bunsen burner but there is *no change in temperature*. There is a change of state — the ice is melting into water. The thermal energy is being taken in to change state.

From C to D, the temperature rises from 0°C to 100°C. There is a change of temperature. The thermal energy is being taken in to increase the temperature.

From D to E, the temperature remains constant at 100°C. There is *no change in temperature* even though thermal energy is still being absorbed. There is a change of state — the water is boiling and changing into steam. The thermal energy is being taken in to change state.

Why is energy needed when a substance changes its state? The kinetic model of matter can explain this.

During **melting**:

The particles in a solid are held in fixed positions by strong bonds. Energy is needed to break the bonds. When the bonds are broken, the particles can move out of their fixed positions and are slightly further apart from each other. The solid has melted. Melting takes place at the melting point without a change in temperature. From Figure 9.14, you can see that the melting point of pure water is 0°C.

The **melting point of pure water** at standard atmospheric pressure of 1 atmosphere is **0°C**.

During **boiling**:

The particles in a liquid have strong forces between them. Energy is needed to break the bonds and separate the particles further apart. Energy is also required for the particles to overcome the atmospheric pressure in order to escape into the air. When these happen, the liquid has boiled. Boiling takes place at the boiling point without a change in temperature. From Figure 9.14, you can see that the boiling point of water is 100°C.

The **boiling point of pure water** at standard atmospheric pressure of 1 atmosphere is **100°C**.

We have seen how energy is absorbed when a solid melts and a liquid boils. What do you think happens to this energy when a liquid solidifies (i.e. freezes) and a gas condenses?

During **condensation**:

The reverse of boiling occurs. When a gas condenses into a liquid, forces pull the particles closer and energy is released.

During **solidification** (freezing):

The reverse of melting occurs. Strong forces pull the particles in a liquid into fixed positions to form a solid. Energy is released.

Figure 9.15 shows the graph for condensation and solidification.

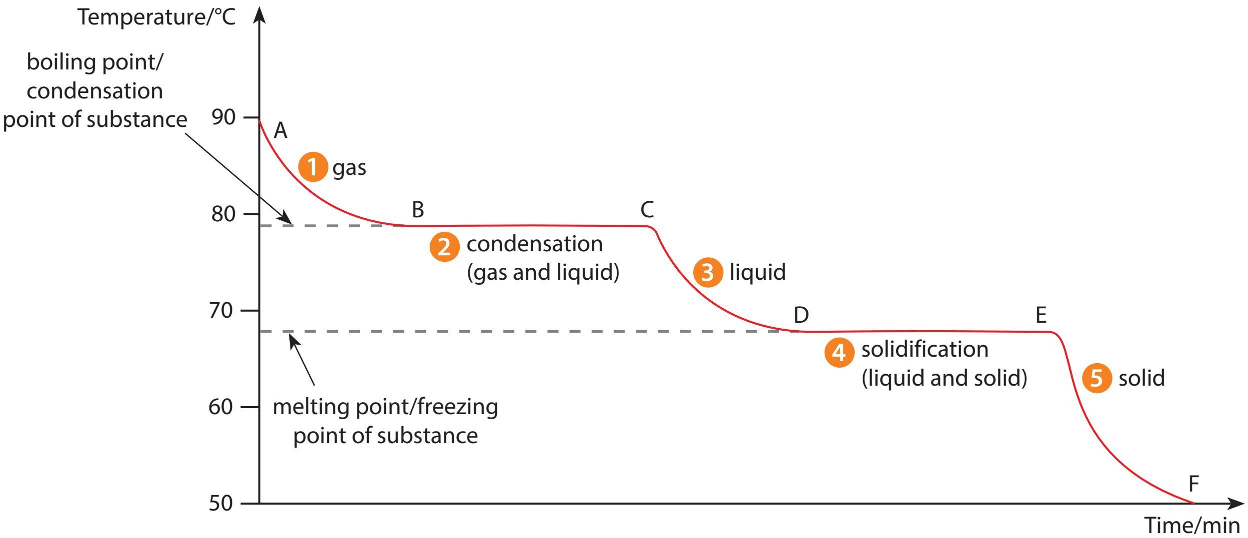


Figure 9.15 *Graph showing the changes of state as matter loses heat*

ENRICHMENT *INFO*

The higher you go above sea level, the lower the atmospheric pressure becomes. This causes water to boil at a lower temperature. On Mount Everest, water boils at about 70°C.

In cold countries, the air warms up before it snows. This is because thermal energy is released by water as it freezes.

A burn from steam at 100°C is more painful than a burn from boiling water. This is because the steam releases more thermal energy on condensing than water cooling from its boiling point.

What is evaporation?

If you observe a floor that has just been mopped, you will notice that the wet surface of the floor soon dries up. The thin layer of water on the surface of the floor has evaporated. Evaporation, like boiling, involves a change of state from liquid to gas.

The kinetic theory of matter explains how evaporation occurs (Figure 9.16).

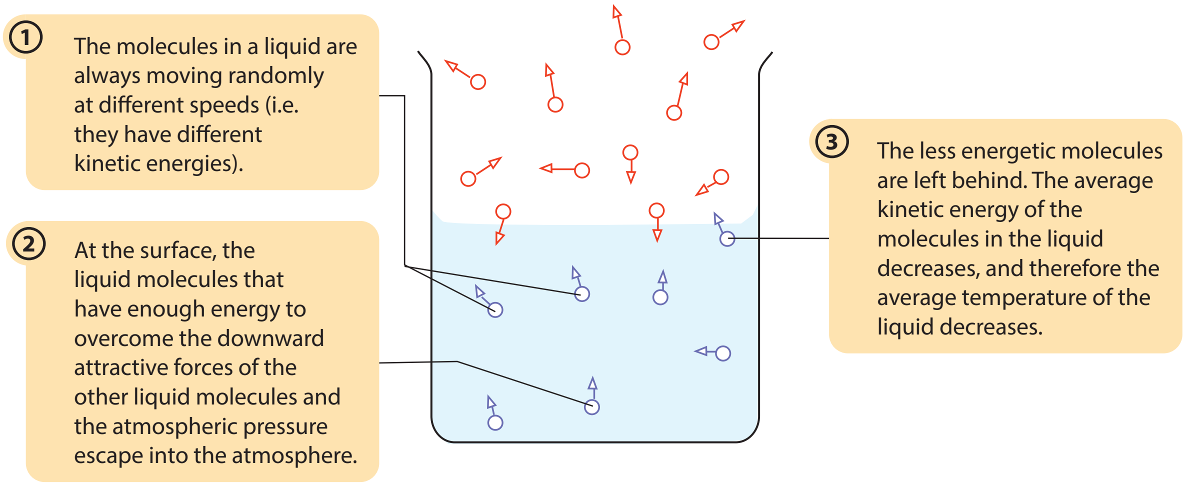


Figure 9.16 *How evaporation occurs*

Evaporation causes cooling

When you step out of a swimming pool on a windy day, you feel cold. This is because the water is evaporating from your skin surface, which results in a decrease in temperature.

Figure 9.17 *The girl feels cold due to the cooling effect of evaporation.*

S Why does evaporation cause cooling?

On a hot day, your body perspires. The sweat evaporates from the surface of your skin. During the evaporation process, water molecules with enough kinetic energy escape into the air. These water molecules have to overcome the attractive forces among themselves as well as the pressure of the atmosphere.

The fastest moving molecules escape into the air, leaving behind the molecules with lower kinetic energy. The average kinetic energy of the water molecules in the perspiration thus decreases, resulting in a lower temperature. The evaporated water molecules carry away the body's latent heat into the air, cooling the body down.

ENRICHMENT *ACTIVITY*

Drinking bird toy

The drinking bird is a toy that rocks to and fro, repeatedly dipping its beak into a glass of water.

In groups, use the Internet to research the drinking bird. Use the key phrases 'drinking bird', 'dipping bird' or 'drinking duck'.

Write a series of steps to explain how it works. Your report should include the process of evaporation.

Share your findings to the rest of the class.

Let's Investigate 9C

Objective
To demonstrate that evaporation causes cooling

Materials
A laboratory thermometer (or a temperature sensor connected to a data logger), some absorbent tissue paper, a beaker of water at room temperature, retort stand and clamp, some adhesive tape or a rubber band, a cold air fan

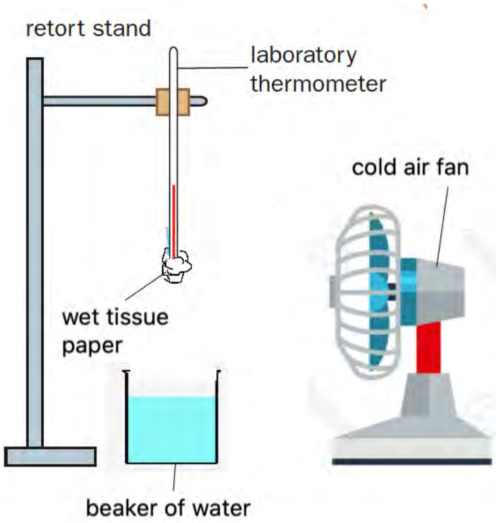


Figure 9.18 Evaporation causes cooling

Procedure
- Cover the thermometer bulb in tissue paper and attach it with adhesive tape or a rubber band.
- Dip the thermometer bulb covered with tissue paper into the water.
- Clamp the thermometer on a retort stand so the bulb is in front of the fan.
- Note the initial temperature.
- Blow cold air over the thermometer bulb for three minutes.
- Note the final temperature.

Observation and discussion
After three minutes the temperature drops by several degrees. The water evaporates into water vapour. This change of state requires thermal energy which is removed from the thermometer, causing it to cool. The cold air fan increases the rate of evaporation. This shows that the evaporation of the water causes cooling.

LINK PWB

Practical 9C, pp. XX–XX

What is the difference between evaporation and boiling?

Boiling and evaporation both involve a liquid becoming a gas and require thermal energy. Boiling occurs throughout the liquid when it reaches its boiling point, while evaporation occurs at all temperatures. The differences are summarised in Table 9.2.

Table 9.2 Differences between boiling and evaporation

Boiling	Evaporation
• Occurs at a particular temperature	• Occurs at any temperature
• Relatively fast	• Relatively slow
• Takes place throughout the liquid	• Takes place only at the liquid surface
• Bubbles are formed in the liquid	• No bubbles are formed in the liquid
• Temperature remains constant	• Temperature may change
• External thermal energy source required	• External thermal energy source not required

QUICK CHECK

Thermal energy is given out when a gas condenses into a liquid and taken in when a liquid changes into a gas.

True or false?

Factors that affect the rate of evaporation are shown in Figure 9.19.

Rate of evaporation is affected by

Temperature

Although evaporation can occur at any temperature, raising the temperature of the liquid will increase the rate of evaporation. A warmer liquid means that a greater number of molecules at the surface layer are energetic enough to escape.

Surface area of the liquid

The rate of evaporation increases when a larger area of liquid is exposed. This is because evaporation only takes place at the exposed surface of a liquid. A larger exposed surface area means more molecules can escape from the liquid.

Movement of air

Moving air removes the liquid molecules as soon as they escape from the liquid surface. This makes the air surrounding the liquid drier. Therefore, the rate of evaporation increases when the surrounding air is moving.

Figure 9.19 What affects the rate of evaporation?

Let's Practise 9.3

1 Explain why spraying perfume on the skin produces a cooling effect.
2 Explain why energy is needed to turn a solid into a liquid.
3 S Explain why puddles evaporate more quickly on a warm day than a cold day.
4 S Give two factors that make wet clothes on a washing line dry more quickly.
5 S Give one similarity and one difference between evaporation and boiling.
6 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK

Exercises 9C–9D, pp. XX–XX

Exercise 9E Let's Practise, p. XX

Let's Map It

THERMAL ENERGY

THERMAL ENERGY → causes → Thermal expansion

THERMAL ENERGY → increases → Internal energy

Internal energy → causes → Temperature rise; Changes of state

Thermal expansion
- Particles move further apart
- Gases expand more than liquids
- Liquids expand more than solids

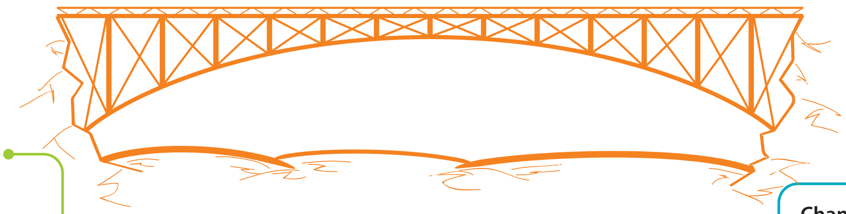
Applications
- Shrink fitting to join metals
- Liquid-in-glass thermometers

Effects
- Expansion of bridges
- Expansion of rails

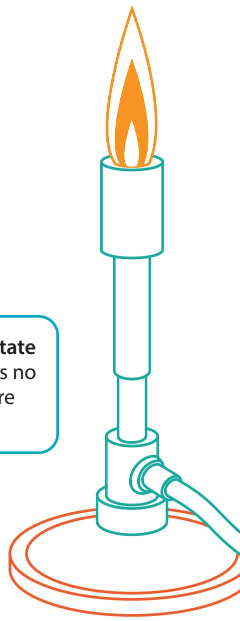
Temperature rise
- S which depends on the specific heat capacity of a substance: $c = \frac{\Delta E}{m\Delta\theta}$

can be used to

S Measure specific heat capacity of solids and liquids

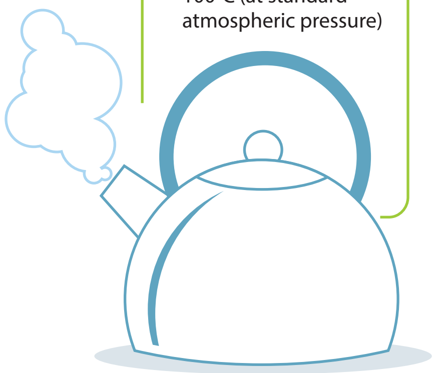


Melting
- Solid to liquid
- Requires energy
- Melting point of pure water = 0°C (at standard atmospheric pressure)

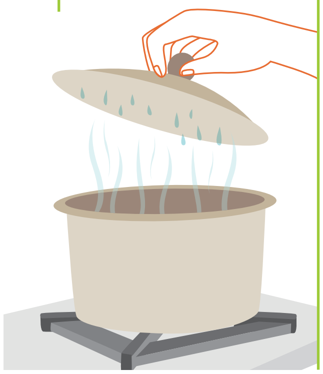


Changes of state (when there is no temperature change)

Boiling
- Liquid to gas
- Requires energy
- Occurs at boiling point
- Boiling point of pure water = 100°C (at standard atmospheric pressure)



Condensation
- Gas to liquid
- Gives out energy

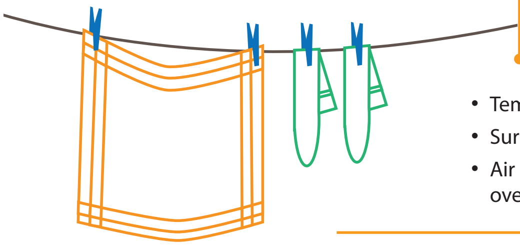


Solidification
- Liquid to solid
- Gives out energy

Evaporation
- Liquid to gas
- Requires energy
- Occurs at any temperature
- Causes cooling

affected by

- Temperature
- Surface area
- Air movement over a surface



Let's Review

Section A: Multiple-choice Questions

1 When a solid is melting, the temperature remains constant even though thermal energy is being supplied. Which of the following explains this observation?

- **A** The energy is used to break the bonds between the particles.
- **B** The solid is not absorbing any thermal energy.
- **C** The solid molecules are moving faster.
- **D** The solid is giving out thermal energy.

2 Which statement is true about internal energy?

- **A** The internal energy of an object is zero at 0°C.
- **B** When thermal energy is supplied to an object, its internal energy decreases.
- **C** An object at a high temperature has less internal energy than the same object at a low temperature.
- **D** The internal energy of an object is the total energy of all of the particles of the object.

3 Which statement is correct?

- **A** When a liquid is heated, the molecules move slower.
- **B** When a liquid is heated, the molecules expand.
- **C** When a liquid is cooled, it contracts.
- **D** When a liquid is heated, its volume decreases.

4 S When a 0.24 kg brass cylinder is heated using a 2.0 kW heater, its temperature increases from 30°C to 100°C in 3.2 s. What is the specific heat capacity of brass?

A 125 J/(kg K) **B** 169 J/(kg K)
C 381 J/(kg K) **D** 400 J/(kg K)

5 S Which statement is correct?

- **A** Evaporation causes cooling.
- **B** Evaporation occurs at the boiling point.
- **C** Evaporation occurs when a gas turns into a liquid.
- **D** Evaporation occurs more slowly at higher temperatures.

Section B: Short-answer and Structured Questions

1 **(a)** Outline a demonstration you could do to show that gases expand when they are heated.
(b) Describe **one** use of the fact that liquids expand when they are heated.
(c) Explain how bridges can be built to withstand damage from expansion in hot weather.

2 Some solid wax at room temperature was heated until it melted. Then, its temperature was taken every minute as it cooled down back to room temperature. Figure 9.20 shows a graph of the results.

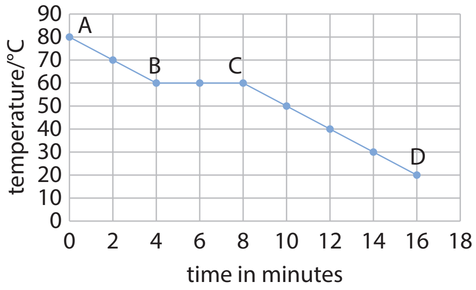


Figure 9.20

(a) Explain what is happening to the wax during
 (i) A to B;
 (ii) B to C;
 (iii) C to D.
(b) Deduce the melting point of wax from this result.

3 S An electric kettle is rated at 25 W. Calculate the
(a) quantity of thermal energy generated in 2 s;
(b) rise in temperature of 150 g of water if the electric kettle is switched on for five minutes and the specific heat capacity of water is 4000 J/(kg K).

4 S The experimental set-up shown in Figure 9.21 was used to determine the specific heat capacity of an unknown metal block.

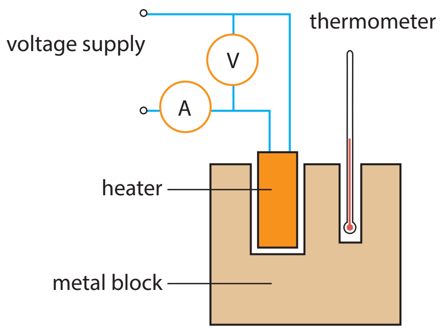


Figure 9.21

The circuit is switched on for a time interval of 500 seconds and the following readings were obtained:

Change in temperature = 50°C

Mass of metal block = 1 kg

Ammeter reading = 5 A

Voltmeter reading = 8 V

Using the above data, calculate the specific heat capacity of the unknown metal block.

CHAPTER

10 Transfer of Thermal Energy

PHYSICS WATCH

Scan this page to watch a clip on how emperor penguins conserve thermal energy.

QUESTIONS

- Observe the body covering, body shape, body size and behaviour of the penguins and discuss how penguins have adapted for a very cold climate.
- Which other animals live in cold countries and how have they adapted?
- How do Arctic explorers or skiers protect themselves in icy weather?

Emperor penguins live in the Antarctic, where temperatures can drop below –50°C. Their bodies have several adaptations to allow them to survive in this extreme cold climate. These adaptations reduce thermal energy transfer from the bodies of the penguins to their surroundings, allowing them to keep warm. They also huddle together and take turns to be in the middle of the huddle. The ways in which thermal energy is transferred will explain how these adaptations work.

10.1 Transfer of Thermal Energy

In this section, you will learn the following:

- Know that thermal energy is transferred from a region of higher temperature to a region of lower temperature.

Why does an object feel hot or cold?

① Prepare three small pails of water labelled P, Q and R at 10°C, 37°C and 50°C respectively.

↓

② Place both your hands in pail Q. Do your hands feel warm or cold?

↓

③ Now, place your right hand in pail P and your left hand in pail R. Do your hands feel warm or cold?

Figure 10.1 *In which pail would your hand feel warm? In which pail would it feel cold?*

Try the activity shown in Figure 10.1. Your hands would feel neither hot nor cold in pail Q. This is because the water in pail Q is at the same temperature as your body temperature — your hands and the water are at *thermal equilibrium*. There is no net gain or loss of thermal energy between your hands and the water.

However, since the temperature of the water in pail R is higher than your body temperature, thermal energy flows from the water to your left hand. Your left hand gains thermal energy from the water, and hence feels warm. Can you now explain why your right hand feels cold?

Thermal energy always flows from *a region of higher temperature* to *a region of lower temperature*. Net flow of thermal energy occurs only when there is a *difference in temperature*.

Thermal energy may be transferred through three processes: conduction, convection and radiation. Which of these processes is involved in the thermal energy transfer between your hand and the water?

10.2 Conduction

In this section, you will learn the following:

- Describe experiments to demonstrate the properties of good thermal conductors and bad thermal conductors (thermal insulators).
- S Know that there are many solids that conduct thermal energy better than thermal insulators but do so less well than good thermal conductors.
- S Describe thermal conduction in all solids.
- S Describe why thermal conduction is bad in gases and most liquids.

How good are different materials at conducting thermal energy?

Have you ever touched a metal spoon that has been left in very hot water?

If you have, you will find that the metal spoon feels hot. This is because thermal energy travels well through metals. This transfer of thermal energy through a solid from the hotter region to the colder region is known as *conduction*.

Conduction is the transfer of thermal energy through solids.

Some materials are better thermal conductors than others. Let us find out what materials are good thermal conductors and what materials are bad thermal conductors in Let's Investigate 10A.

Let's Investigate 10A

Objective
To investigate the transfer of thermal energy through solids

Materials
Bunsen burner, tripod stand, four rods of the same dimensions but made of different materials (copper, steel, aluminium and glass), stopwatch, wax, drawing pins

Procedure

1. Drip a few drops of melted wax on one end of the copper rod.
2. Place a drawing pin on top of the melted wax and allow the wax to harden.
3. Repeat steps 1 and 2 with the other rods. Take note to place the drawing pins at the same position for each rod.
4. Place the rods on a tripod stand. Ensure that the ends of the rods are aligned.
5. Place the Bunsen burner under the ends of the rods without the drawing pin (Figure 10.2).
6. Record the time taken for the drawing pin to fall from each rod in the Table 10.1.

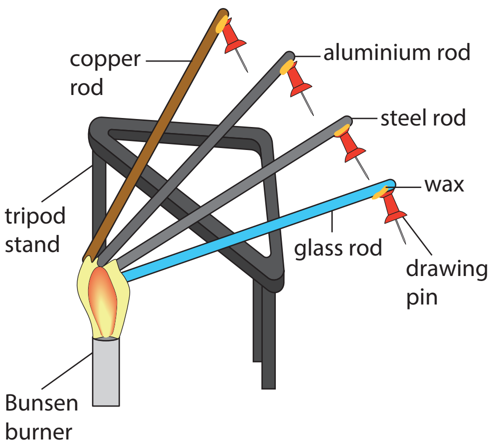


Figure 10.2 Comparing conduction in different materials

Table 10.1

Rod	Copper	Steel	Aluminium	Glass
Time taken / s				

Observation

The time taken for the drawing pin to fall was the shortest for the copper rod, and the longest for the glass rod.

Discussion and conclusion

1 For the drawing pins to fall, the wax on the four rods must melt. The wax melted because thermal energy was transferred from the ends of the rods heated by the Bunsen burner (the hotter region) to the ends of the rods at room temperature (the cooler region). The transfer of thermal energy through the rods occurred without any flow of the material the rods were made of. This means that thermal energy was transferred by conduction.

2 The time taken for the drawing pin to fall for each of the four rods was different. This shows that different materials conduct thermal energy at different rates. The time taken is the shortest for copper and longest for glass. From this, we can conclude that copper is the best and glass is the worst thermal conductor among the four materials.

PWB LINK

Practical 10, pp. 67–72

The **thermal conductivity** of a material is dependent on how quickly thermal energy is transferred from the hotter end to the colder end (Figure 10.3). Materials that can transfer thermal energy quickly are good thermal conductors, while materials that transfer thermal energy slowly are bad thermal conductors.

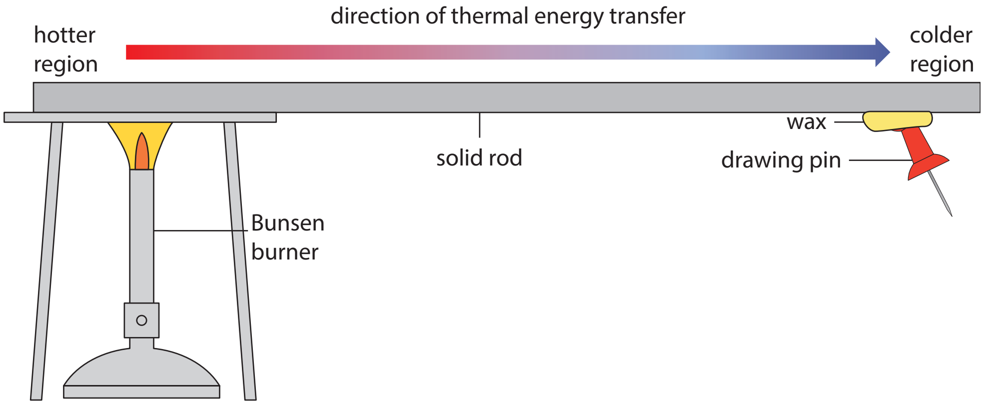


Figure 10.3 Thermal energy is conducted from the hotter end to the colder end.

PHYSICS WATCH

Scan this page to explore factors affecting the rate of thermal conduction.

In general, metals are good thermal conductors. Non-metals such as glass plastic, wood, wool, air and water are bad thermal conductors. Bad thermal conductors are also known as thermal **insulators**.

S There is a big difference between the **thermal conductivity** of metals and non-metals. However, there are also materials that conduct thermal energy not as well as thermal conductors but better than thermal insulators. Examples of such materials can be found in Table 10.2.

Table 10.2 Comparing the thermal conductivity of different materials

Best conductor → Worst conductor							
Diamond	Copper	Steel	Ice	Polythene	Fibreglass	Polystyrene	Air
Worst insulator → Best insulator							

Fibreglass and polystyrene are good thermal insulators because they contain air.

ENRICHMENT ACTIVITY

Touch the surface of a metal frying pan and an empty plastic lunch box. Do the temperatures feel the same?

Now place a similar-sized ice cube on top of each surface. Predict which ice cube will melt first. Were you right in your prediction? Explain your observations to the class.

> **LINK**
>
> Recall from Chapter 8 that matter is made up of tiny particles.

> **HELPFUL NOTES**
>
> An atom contains electrons within it. The electrons in most non-metals are attached to one atom. In metals, however, some electrons are free to move.

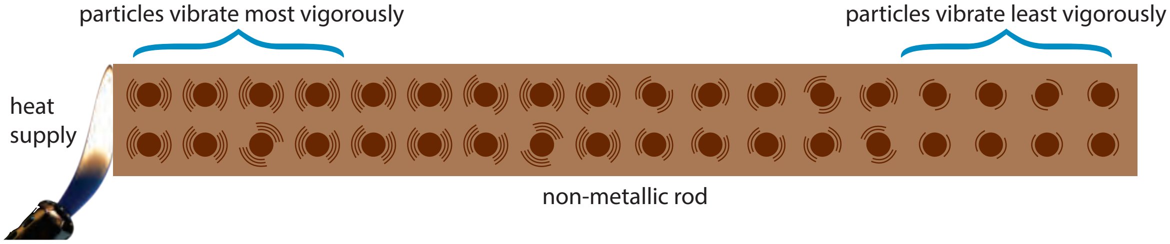
How does conduction work?

Why is the rate of conduction much faster in metals than in non-metals?

Both metals and non-metals are made up of tiny particles (atoms or molecules). The difference is that metals contain many *free electrons*, while non-metals do not. These free (or *delocalised*) electrons are not firmly attached to one atom but can move randomly among the atoms of the metal. We have learnt that particles vibrate about a fixed position in solids. This vibration is also known as *lattice vibration*.

Figure 10.4 describes the process of conduction in non-metals and metals. Note that in metals, thermal energy is transferred through lattice vibrations of particles and movement of free electrons. In non-metals, only lattice vibrations of particles takes place. This explains why metals are better thermal conductors.

Non-metals



①
- The particles (atoms or molecules) at the hot end vibrate vigorously about their fixed positions.

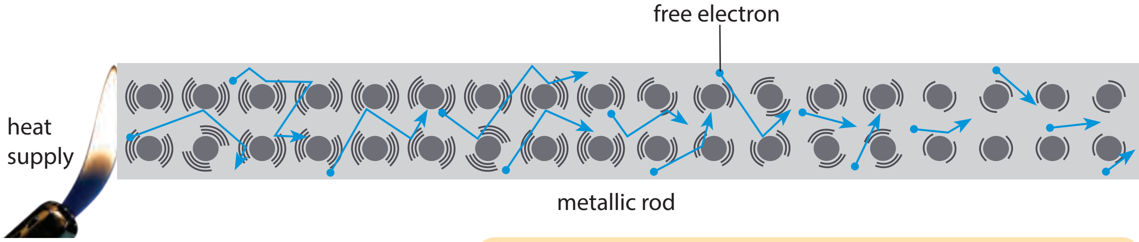
②
- They collide with neighbouring particles, making them vibrate more vigorously. (The kinetic energy of the vibrating particles at the hot end is transferred to the neighbouring particles.)
- The neighbouring region of the rod becomes hot.
- Thermal energy has been transferred without the transfer of particles.

③
- Eventually, the particles at the cooler end of the rod vibrate vigorously.
- The cooler end of the rod becomes hot.

(a) Thermal transfer in non-metals occurs via lattice vibrations of particles.

> **LINK**
>
> Metals are good conductors of thermal energy as well as electricity. The presence of free electrons in metals allow current to flow. You will learn more about this in Chapter 16.

Metals



①
- In addition to the process that takes place in non-metals, another (much faster) mechanism of thermal transfer takes place in metals: free electron diffusion.
- The free electrons at the heated end absorb thermal energy, and hence gain kinetic energy.

②
- The free electrons that gain kinetic energy move at greater speeds, and move to the cooler regions of the rod.
- As these electrons move, they collide with the atoms in the cooler parts of the rod, making them vibrate more vigorously. (Some of the kinetic energy of the moving electrons is transferred to the atoms.)
- Thermal energy is transferred via the motion of the free electrons. The cooler end of the rod becomes hot.

(b) Thermal transfer in metals occurs via lattice vibrations of particles and free electron diffusion.

***Figure 10.4** Transfer of thermal energy in metals and non-metals*

> **QUICK CHECK**
>
> A stone floor feels colder to bare feet than a cloth rug because stone is a better thermal conductor than cloth.
>
> True or false?

Why are liquids and gases bad thermal conductors?

Thermal energy can also be conducted from a hotter region to a colder region in liquids and gases by conduction. But it is not efficient. Can you think why?

We have learnt in Chapter 8 that the particles in liquids and gases are spaced further apart than those in solids. The collisions between the particles are therefore less frequent in liquids and gases. This means that the transfer of kinetic energy from the fast-moving particles (in the hotter region) to neighbouring particles (in the colder region) is slower. This explains why air and water are bad thermal conductors. In the next section, we will learn that how thermal energy is transferred in liquids and gases.

QUICK CHECK

Gases are better thermal conductors than liquids.

True or false?

Let's Practise 10.1 and 10.2

1 How is thermal energy transferred?
2 Why is copper a good material for making a cooking pot?
3 Why do copper cooking pots have plastic handles?
4 S Explain why metals are better thermal conductors than non-metals.
5 S Why is water a bad thermal conductor?
6 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK

TWB

Exercises 10A–10B, pp. XX–XX

10.3 Convection

In this section, you will learn the following:

- Know that convection is an important method of thermal energy transfer in liquids and gases.
- Explain convection in liquids and gases in terms of density changes.
- Describe experiments to illustrate convection.
- Describe experiments to demonstrate the properties of bad thermal conductors (thermal insulators).

How do liquids and gases transfer thermal energy?

Liquids and gases get hotter by convection.

Convection is the transfer of thermal energy in a fluid (liquid or gas) by means of convection currents due to a difference in density.

Convection in liquids

Water is a transparent liquid and hence, it is difficult to observe convection currents in pure water. Figure 10.5 demonstrates convection currents in water through the help of potassium permanganate crystals, which are purple in colour. These crystals dissolve in the water to form a purple stream.

When the bottom of the flask is heated, the purple streams (shown as purple arrows) rise to the top of the flask. Then, they fan out before sinking back down the sides. The circulating purple arrows represents the convection currents in water.

Convection currents form because of the difference in density in water when heated. When the water at the bottom of the flask is heated, it expands. The expanded water is less dense than the surrounding water because there is more space between the molecules. The warmer, less dense water rises. It cools down at the top of the flask, become denser and sinks down again. This process repeats until the whole flask of water is heated up.

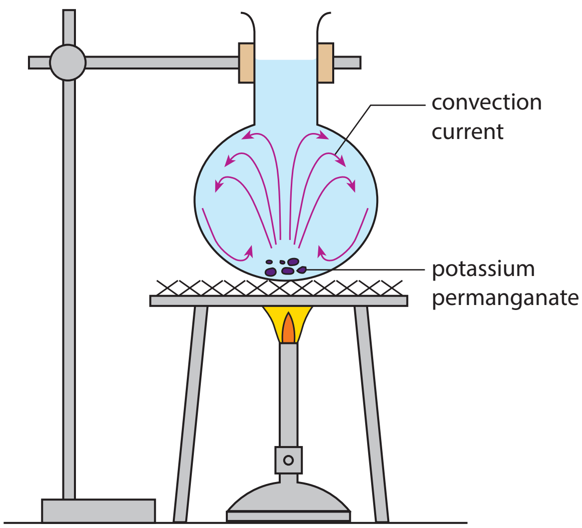


Figure 10.5 *Convection in water*

PHYSICS WATCH

scan this page to watch a clip on convection in water and air.

Convection in gases

Figure 10.6 demonstrates convection currents in air. The incense stick is used to produce smoke that trace the convection currents.

The candle below the chimney on the right is lit. The incense stick is held over the left chimney. As shown by the black arrows, the smoke is drawn down the left chimney, across to the right chimney, and then rises up above the candle. The black arrows show the circulating convection currents in air.

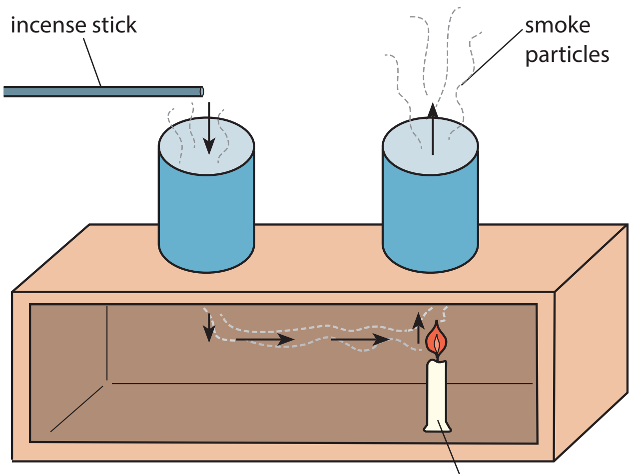


Figure 10.6 *Convection in air*

Convection currents form because of the difference in density in air when heated. When the air above the candle is heated, it expands. As the warm air is less dense than the surrounding air, it rises out of the right chimney. Cooler denser air sinks down the left chimney to take the place left by the warm air, carrying the smoke from the incense stick along. The movement of air forms the smoke trails (indicated by the black arrows) that we observe.

Convection currents occur only in fluids (liquids and gases). They do not occur in solids. This is because convection involves the *bulk movement* of the fluid that carries the thermal energy. This means that for convection currents to occur in a substance, the substance must be able to *flow*.

In solids, the particles are in fixed positions. Hence, solids cannot flow. They can only transfer thermal energy from one particle to another through lattice vibrations (and free electron diffusion in metals) without any bulk movement of the particles (i.e. via conduction).

QUICK CHECK

Hot air balloons rise because hot air is less dense than cold air.

True or false?

Conduction in liquids

Thermal energy transfer through conduction still occurs in liquids, but it is much slower compared to convection. To show that liquids are bad thermal conductors, you have to prevent convection currents from forming. To produce convection, a liquid has to be heated from the bottom, like in Figure 10.5.

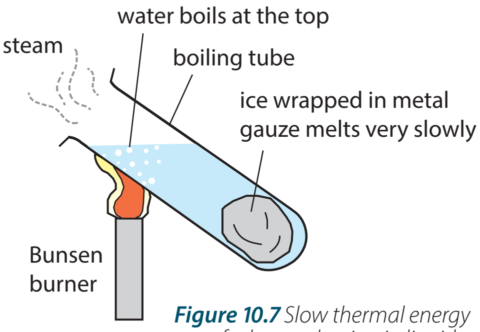


Figure 10.7 *Slow thermal energy transfer by conduction in liquid*

In Figure 10.7, the water in the boiling tube is heated at the top. The only way that the water at the bottom can get hot is by conduction because hot liquids, being less dense, will rise instead of sink to the bottom. An ice cube is wrapped in metal gauze to make it sink to the bottom of the boiling tube. The result is that the water at the top boils while the ice cube at the bottom remains frozen. The transfer of thermal energy by conduction from the hot water at the top of the boiling tube to the ice at the bottom is slow. This shows that water is a bad thermal conductor.

ENRICHMENT
THINK

Still air can be formed by stopping air from moving. Still air is an excellent thermal insulator.

1 Why does the air have to be still?

2 Give an example of something that uses still air for insulation.

Let's Practise 10.3

1 **(a)** What happens to the density of a material when it is heated?

(b) Explain your answer in **(a)**.

2 Describe the formation of convection currents in a liquid.

3 Why does convection occur when gases and liquids are heated but not when solids are heated?

4 Use an experiment to describe why liquids and gases are bad thermal conductors.

5 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK

Exercise 10C, pp. XX–XX

10.4 Radiation

In this section, you will learn the following:

- Know that thermal radiation is infrared radiation and that all objects emit this radiation.
- Know that thermal energy transfer by thermal radiation does not require a medium.
- S Describe experiments to distinguish between good and bad emitters of infrared radiation.
- S Describe experiments to distinguish between good and bad absorbers of infrared radiation.
- Describe the effect of surface colour and texture on the emission, absorption and reflection of infrared radiation.
- S Describe how the rate of emission of radiation depends on the surface temperature and surface area of the object.
- S Know that for an object to be at a constant temperature it needs to transfer energy away at the same rate that it receives energy.
- S Know what happens to an object if the rate at which it receives energy is less or more than the rate at which energy is transferred away.
- S Know how the temperature of the Earth is affected by factors controlling the balance between incoming radiation and radiation emitted from the Earth's surface.

Figure 10.8 *infrared radiation emitted by a human face*

WORD ALERT

Absorb: take in

Emit: give out

What is thermal radiation?

Thermal radiation is also known as infrared radiation. All objects absorb and emit infrared radiation, which is an invisible radiation that carries thermal energy.

Infrared cameras can be used to detect infrared radiation. Figure 10.8 shows the infrared radiation emitted by a human face. The image has been colour-coded. The colours range from white indicating the hottest part, through yellow, orange, red, violet, blue and then black, indicating the coldest part.

Thermal radiation is the transfer of thermal energy in the form of invisible waves called infrared radiation which can travel through a vacuum.

Unlike conduction and convection, infrared radiation can travel through a vacuum. It does not require a medium to travel through. The Earth receives a lot of infrared radiation from the Sun as space is a vacuum (Figure 10.9).

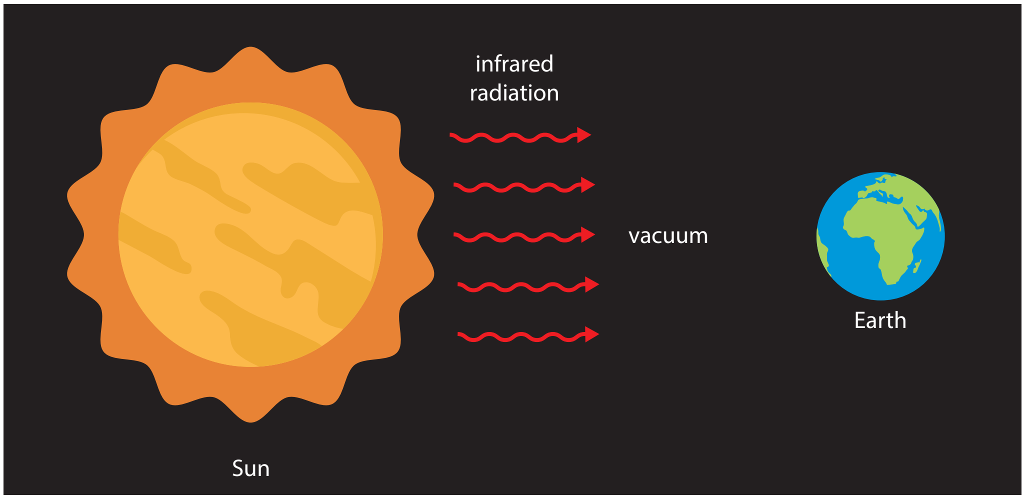


Figure 10.9 *Thermal energy from the Sun is transferred to the Earth by thermal radiation only.*

ENRICHMENT INFO

Infrared Thermometer

An infrared thermometer measures the temperature of a surface using the infrared radiation the surface emits. As shown in Figure 10.10, the thermometer is pointed near a person's forehead. Infrared radiation emitted by the person is measured and shown as a temperature reading on the thermometer.

The advantage of using this thermometer is that it works from a distance. This reduces the chance of transferring harmful bacteria or viruses from one person to another when the thermometer is shared.

Figure 10.10 *An officer measuring the temperature of the girl using an infrared thermometer*

How can we investigate emission and absorption of different surfaces?

Emission

When objects emit infrared radiation, the temperature of the object decreases, and the object cools down. Good emitters will give out infrared radiation at a faster rate and cool down more quickly than bad emitters. Let us investigate the emission of infrared radiation through different surfaces (Figure 10.11).

Figure 10.11 shows two tins which were filled with boiling water at the same time.The temperature sensors record the temperature change inside the respective tin.

Figure 10.12 shows the temperature–time graph recorded by the data logger. The temperature of the dull black tin fell at a faster rate than that of the shiny silver tin. They would eventually both reach room temperature. This shows that dull and black surfaces emit infrared radiation at a faster rate than shiny and silver surfaces.

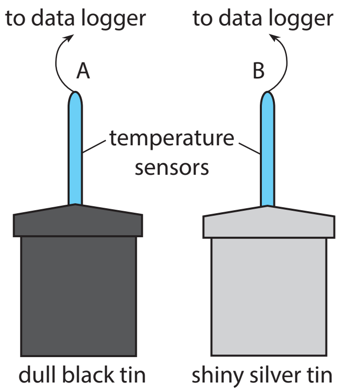


Figure 10.11 *Comparing emission of infrared radiation*

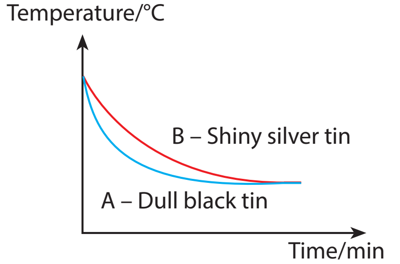


Figure 10.12 *Temperature–time graph*

Absorption

When objects absorb infrared radiation, the temperature of the object increases and the object heats up. Good absorbers will absorb infrared radiation at a faster rate than a bad absorber and heat up more quickly. Let us investigate the absorption of infrared radiation through different surfaces (Figure 10.13).

Figure 10.13 shows two temperature sensors at equal distances from a light bulb. Temperature sensor A is wrapped with aluminium foil. Temperature sensor B is wrapped with aluminium foil painted matte black. When the light bulb is switched on, it emits infrared radiation. This radiation will then be absorbed by the two types of foil. The temperature rise in each type of foil is then recorded in a data logger.

WORD ALERT

Matte: dull and not shiny

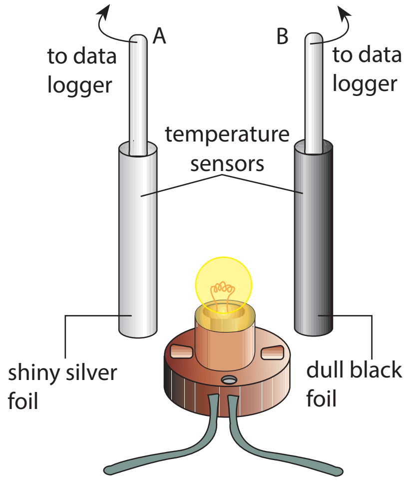


Figure 10.13 *Comparing absorption of infrared radiation*

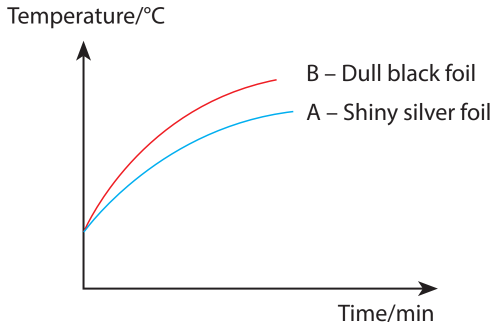


Figure 10.14 *Temperature–time graph*

Figure 10.14 shows the temperature–time graph recorded by the data logger. The temperature rise more quickly for the dull black foil as compared to the shiny silver foil. This shows that the dull black foil absorbs infrared radiation at a faster rate than the shiny silver foil.

From the two experiments, we can conclude that dull black surfaces emit and absorb infrared radiation at a faster rate than shiny silver surfaces. Shiny silver surfaces absorb less and reflect more infrared radiation.

PHYSICS WATCH

Scan this page to watch a clip on absorption and emission of radiation.

What factors affect the emission and absorption of thermal radiation?

The amount of infrared radiation absorbed by or emitted from a surface depends on three factors: surface colour and texture, surface temperature and surface area.

Surface colour and texture

Have you wondered why at the end of a marathon, the runners wrap themselves in what looks like a sheet of tin foil (Figure 10.15)? This foil, also known as a space blanket, was developed by the National Aeronautics and Space Administration (NASA). After a marathon, the body temperature of marathon runners drops drastically. This can cause hypothermia, a serious medical emergency in which the body rapidly loses heat. Space blankets can help to keep them warm by reducing thermal energy emission via infrared radiation. Figure 10.15 shows a marathon runner covered with a space blanket. Using what you have learnt previously in the chapter, can you explain how the space blanket keeps the marathon runner warm?

The space blanket has two shiny surfaces. The shiny outer surface reduces emission of infrared radiation from the runner to the surroundings. The shiny inner surface reflects the infrared radiation back to the runner. These allow the marathon runner to keep himself warm.

From what we have learnt in the earlier section, the amount of infrared radiation absorbed by or emitted from a surface is dependent on the **colour and texture** of the surface.

Dull and black surfaces emit and absorb infrared radiation at a faster rate than shiny and silver surfaces. Shiny and silver surfaces reflect more infrared radiation.

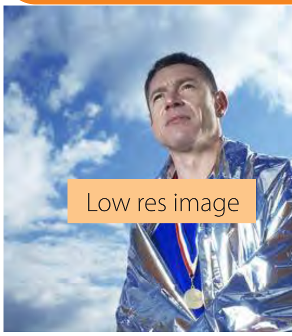


Figure 10.15 *A marathon runner using a space blanket to keep himself warm*

QUICK CHECK

Rooftop solar water heater are painted black because black is a better absorber of infrared radiation.

True or false?

Surface temperature

The higher the temperature of an object's surface relative to the surrounding temperature, the higher the rate of emission of infrared radiation (Figure 10.16).

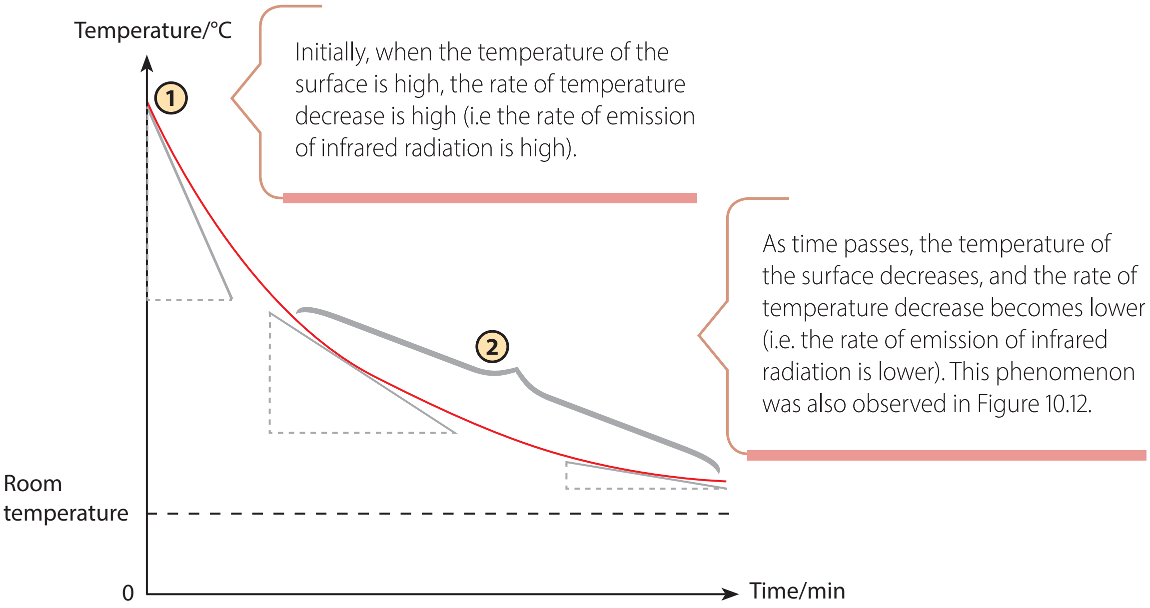


Figure 10.16 *The surface temperature of an object affects its rate of emission of infrared radiation.*

LINK

Recall from Section 10.1 that thermal energy always flows from a region of higher temperature to a region of lower temperature.

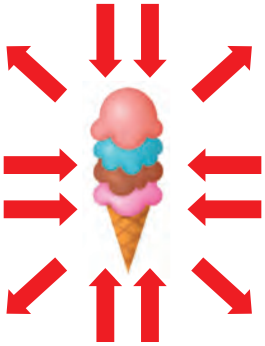
Surface area

If we compare two objects of the same mass and material, but with different surface areas, the object with the larger surface area will emit or absorb infrared radiation at a higher rate.

How does the emission and absorption affect the temperature of an object?

All objects continuously emit and absorb infrared radiation. How will the rates of emission and absorption compare if the object is warming up, cooling down or staying at the same temperature?

If an object absorbs energy at a greater rate than it emits energy, then it is warming up. This will happen if the object is cooler than its surroundings (Figure 10.17 (a)).



- An ice cream outside on a hot day
- Temperature of ice cream = 0°C
- Temperature of surroundings = 30°C
- Infrared radiation absorbed > infrared radiation emitted
- The ice cream warms up.

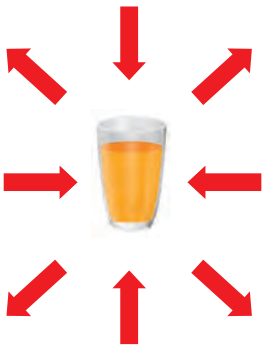
Figure 10.17 (a) *An ice cream warms up as it absorbs more infrared radiation than it emits.*

If an object emits energy at a greater rate than it absorbs energy, then it is cooling down. This will happen if the object is hotter than its surroundings (Figure 10.17 (b)).

- A cup of hot coffee in an air-conditioned room
- Temperature of coffee = 80°C
- Temperature of surroundings = 20°C
- Infrared radiation absorbed < infrared radiation emitted
- The coffee cools down.

Figure 10.17 (b) *A cup of hot coffee cools down as it emits more infrared radiation than it absorbs.*

If the rates of emission and absorption of an object are the same, then the temperature of the object will not change. This will happen if the object is at the same temperature as its surroundings (Figure 10.17 (c)).



- A glass of orange juice at 20°C in a room at 20°C
- Temperature of orange juice = 20°C
- Temperature of surroundings = 20°C
- Infrared radiation absorbed = infrared radiation emitted
- The orange juice is in thermal equilibrium with its surroundings.

Figure 10.17 (c) *A cup of orange juice does not change in temperature as the infrared radiation emitted is the same as the infrared radiation absorbed.*

S The temperature of the Earth is maintained at around 15°C due to the greenhouse effect. The greenhouse effect is a natural process that warms the Earth's surface through a balance of absorption and emission of infrared radiation. This is shown in Figure 10.18.

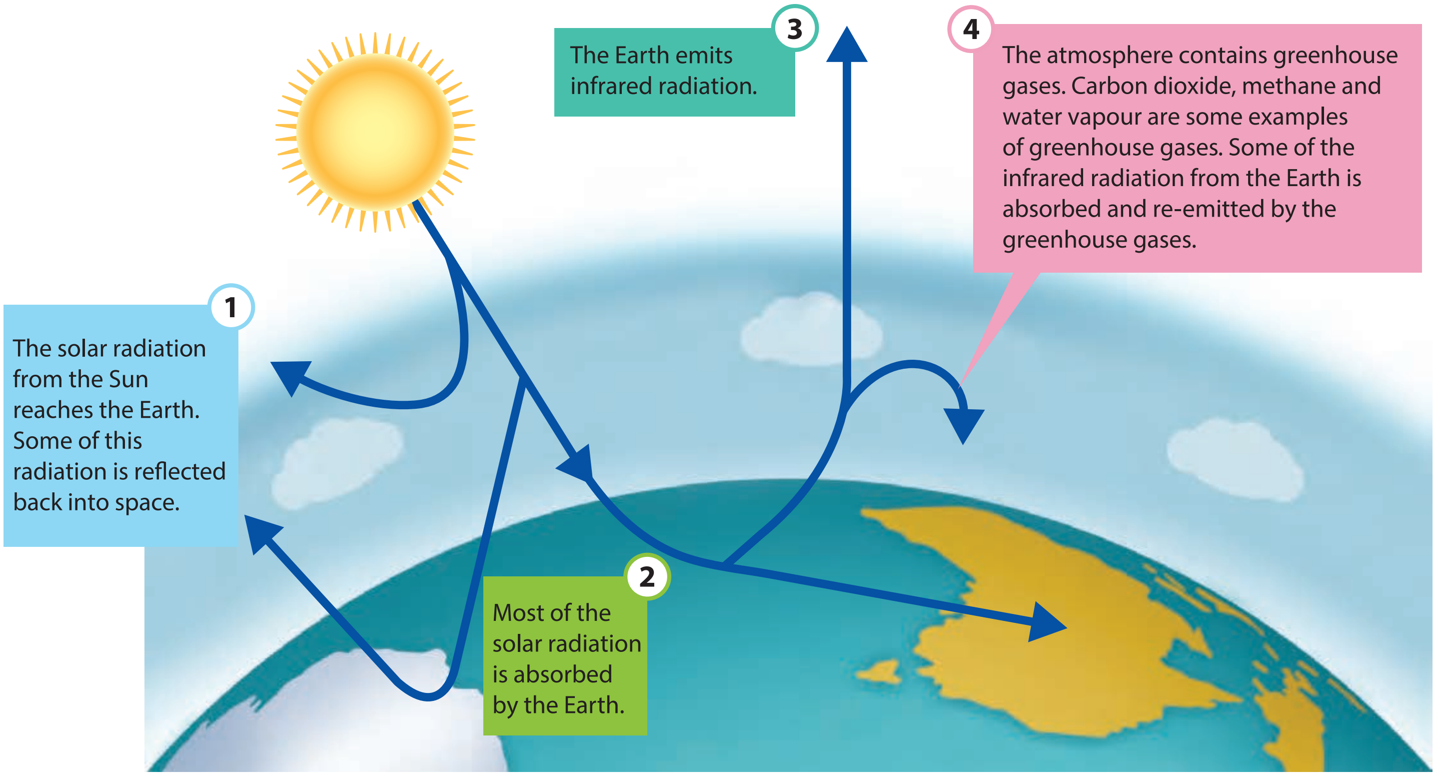


Figure 10.18 *The greenhouse effect is needed to keep the temperature of the Earth suitable for life.*

However, human activity has increased the amount of greenhouse gases in the atmosphere. For example, the use of fossil fuels has increased the amount of carbon dioxide gas. Agriculture, such as rearing of cattle, has increased the amount of methane. The increase in greenhouse gases results in more thermal energy being radiated back to the Earth. This is causing the temperature of the Earth to increase, causing global warming.

Let's Practise 10.4

1 Identify how thermal energy is transferred from the Sun to the Earth. Explain why thermal energy from the Sun cannot reach the Earth by other processes.

2 Why would you feel hot if you wore dark-coloured clothes on a hot day?

3 Describe an experiment to find out how surface colour and texture affects the absorption and emission of infrared radiation.

4 S State three factors that affect the rate of transfer of thermal energy by radiation.

5 S Using thermal energy transfer(s), explain what causes the change in the following objects:

(a) A piece of ice cube from the freezer melts when placed on the table.

(b) A car heats up after being parked under the hot Sun.

6 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

TWB LINK
Exercise 10D, pp. XX–XX

10.5 Applications and Consequences of Thermal Energy Transfer

In this section, you will learn the following:

- Explain some of the basic everyday applications and consequences of conduction, convection and radiation.
- S Explain some of the complex applications and consequences of conduction, convection and radiation.

One method of thermal energy transfer

Consequence of conduction

Have you noticed that a metal object feels colder to the touch than a plastic object even if they are at the same temperature (Figure 10.19)?

The metal pole is a good thermal conductor. It conducts thermal energy away from your warm hand, making it feel cold. Plastic is a good thermal insulator and does not conduct thermal energy away from your hand.

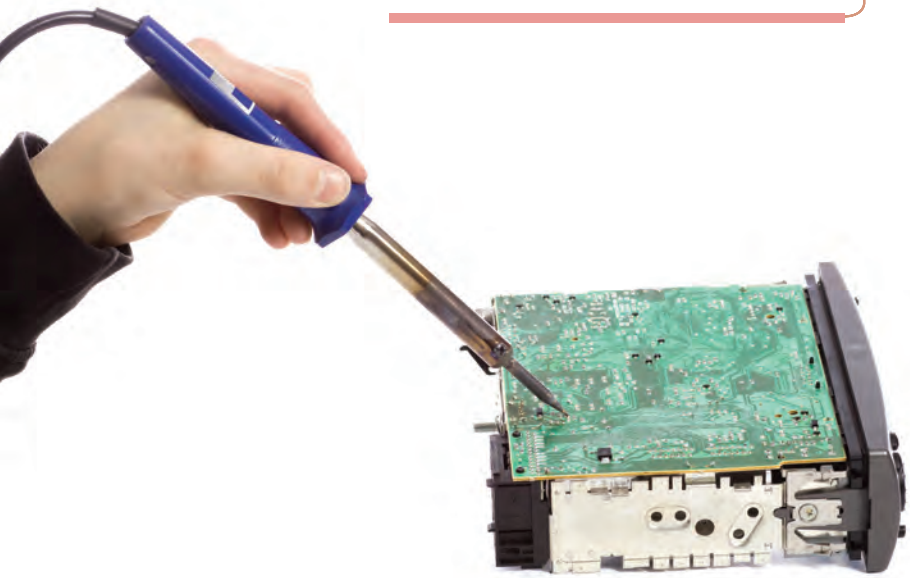
Figure 10.19 *Your hand feels cold when you touch a metal pole.*

Applications of good thermal conductors

To transfer thermal energy quickly through a substance, good thermal conductors are used. Metals are examples of good thermal conductors. They are commonly used to make the items shown in Figure 10.20.

Cooking utensils

Saucepans, woks and pots are usually made of aluminium or stainless steel.



Soldering irons

Soldering irons are used to build and repair electronic circuits. The tips are made of copper as it is a very good thermal conductor and quickly transfers thermal energy from the soldering iron to the electronic circuit.

Figure 10.20 *Examples of items that make use of the good thermal conductivity of metals*

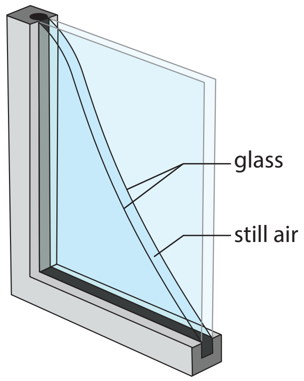
Applications of bad thermal conductors (good thermal insulators)

To reduce thermal energy from being transferred quickly, good thermal insulators are used. Figure 10.20 shows some common uses of good thermal insulators.

Handles of cooking utensils

Handles of cooking utensils like saucepans are made of wood or plastics.

This protects our hands from getting hurt from touching a hot saucepan on the stove.



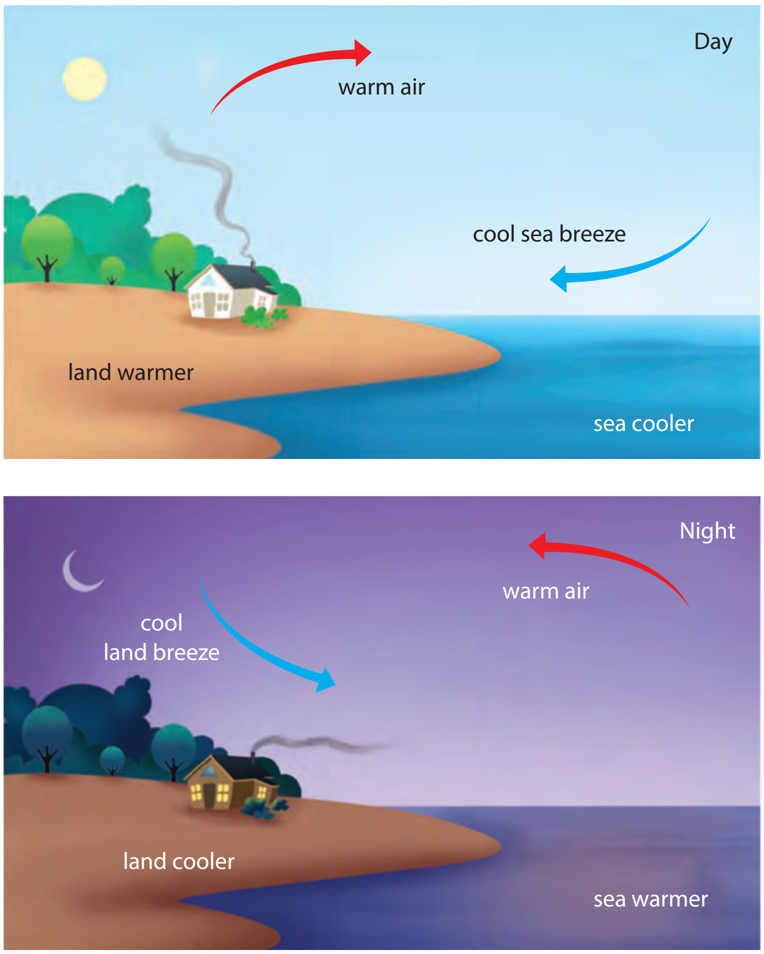
Double-glazed window

A double-glazed window has a layer of still air trapped between two panes of glass. Still air is a good thermal insulator and reduces the thermal energy passing through the window.

Figure 10.21 *Examples of items that use good thermal insulators to reduce thermal energy transfer*

Consequence of convection

There is often a breeze near the sea when there is no wind inland. The direction of the breeze is dependent on the time of the day as shown in Figure 10.22.



During the day, the sand on the beach heats up more quickly than the sea. The warmer air above the sand rises as it is less dense than its surroundings. Cooler air from the sea will be drawn in to take its place. This sets up a convection current, creating a sea breeze.

In the evening, the sand cools more quickly than the sea. The warmer air above the sea rises as it is less dense than its surroundings. Cooler air from the land will be drawn in to take its place, setting up convection currents in the opposite direction. This creates a land breeze.

Figure 10.22 *Convection currents near the sea*

Applications of convection

Figures 10.23 and 10.24 show some examples of appliances that use convection to function.

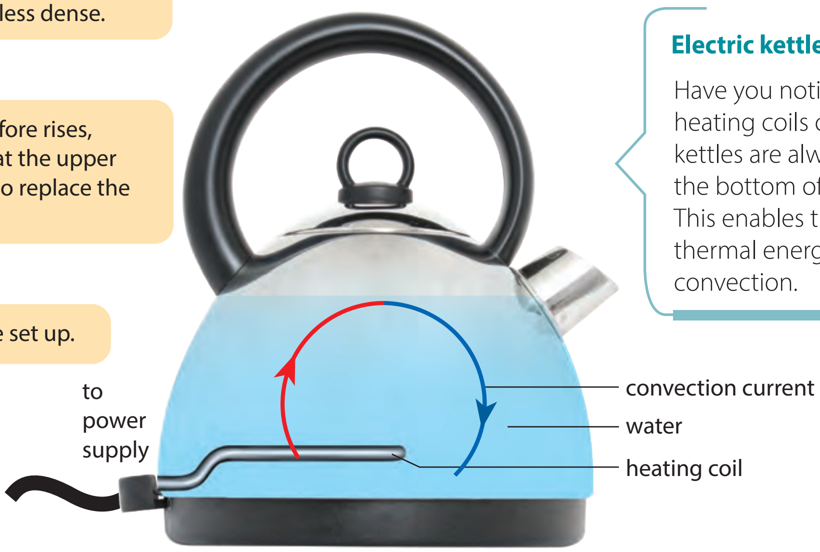
① When the power is switched on, the water near the heating coil heats up, expands and becomes less dense.

↓

② The heated water therefore rises, while the cooler water at the upper part of the kettle sinks to replace the heated water.

↓

③ Convection currents are set up.



Electric kettles

Have you noticed that the heating coils of electric kettles are always placed at the bottom of the kettle? This enables the transfer of thermal energy in water by convection.

Figure 10.23 *The convection currents in the electric kettle enable the water in the kettle to be heated up more quickly and evenly.*

Air conditioners

Air conditioners are used to cool houses in warm weather. An air conditioner is always installed near the ceiling of a room. It sends cool, dry air into the room. As cool air is denser, it sinks. The warm air below, being less dense, rises and is drawn into the air conditioner where it is cooled. Hence, the circulating convection currents cool the room.

Hot water radiators

Hot water radiators are often used to heat houses in cold weather. Even though they are named "radiators", they heat the air in the room mainly by convection. The air around a radiator is heated up by the radiator and rises. The surrounding cold air is drawn into the radiator, where it is heated up. The circulating convection currents heat up the room.

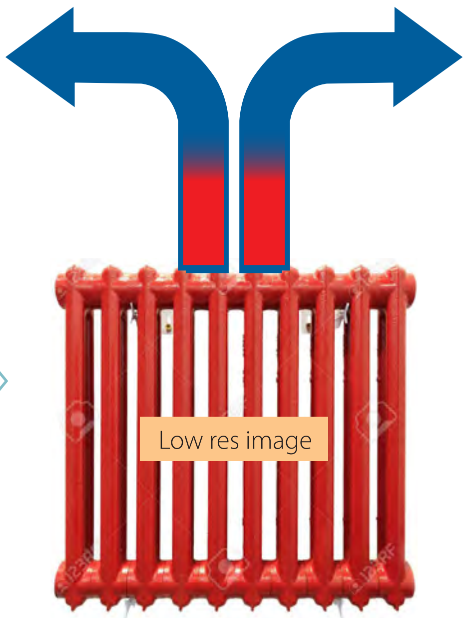


Figure 10.24 *The convection currents by an air conditioner and a radiator help to control the temperature of a room during different parts of the year.*

Consequence of radiation

Infrared radiation from the Sun travels through the vacuum of space and the atmosphere to warm the Earth. The Earth's surface absorbs the radiation, warms up and emits infrared radiation back into space (Figure 10.25).

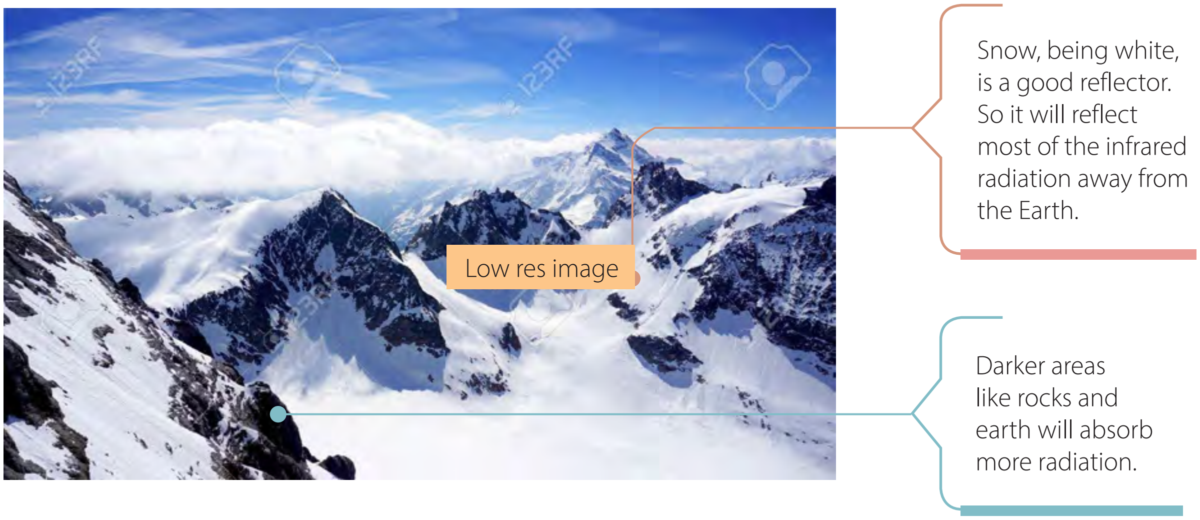


Figure 10.25 *Snow on mountains help to reflect radiation from the Sun.*

Due to global warming, snow is melting at an increasing rate. This can reduce the amount of radiation reflected from the Earth, causing the Earth to warm up even more.

Application of radiation

Greenhouses are used in cold climates to trap thermal energy (Figure 10.26). The temperature of a greenhouse is higher than the temperature outside. This enables plants to grow when it would normally be too cold for them.

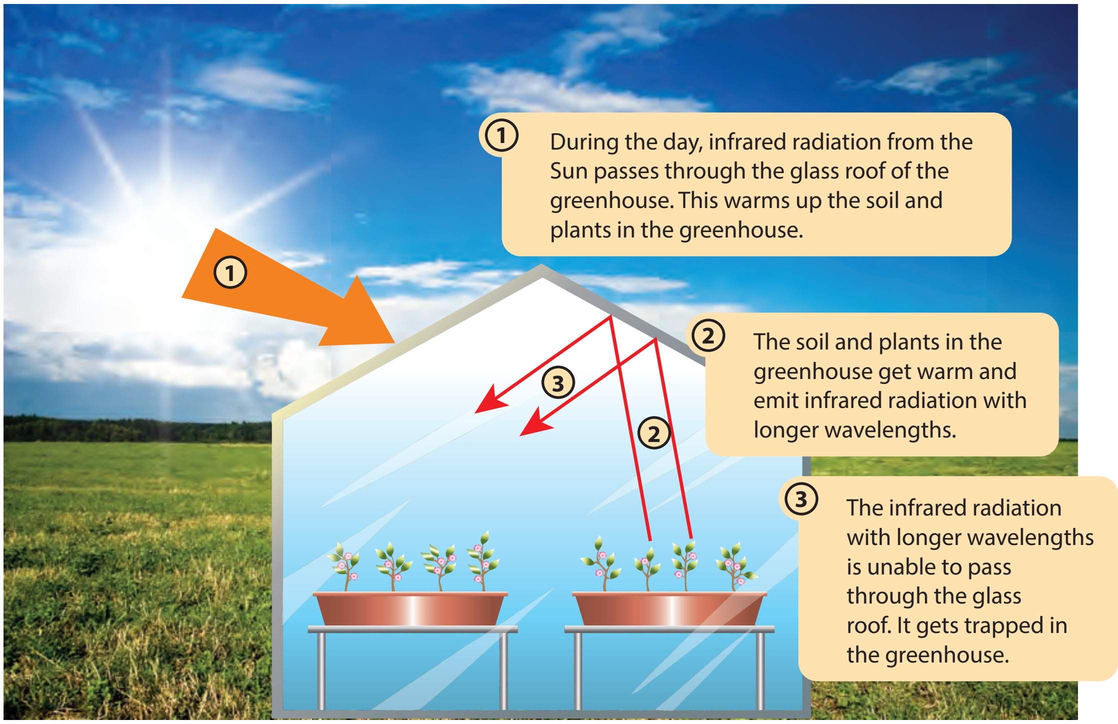


Figure 10.26 *Infrared radiation gets trapped in the greenhouse.*

Figure 10.27 Boiling water over a campfire

Multiple methods of thermal transfer

Cooking on a wood fire

Wood burns and releases thermal energy. Thermal energy is then transferred via conduction, convection and radiation to the surroundings. Figure 10.27 shows a pot of water being boiled over burning wood.

The bottom of the metal pot is in contact with the fire so thermal energy will be transferred to the bottom of the metal pot through *conduction*. The ground underneath the fire will also get hot by conduction.

The flames will emit *infrared radiation*. If you place your hands close to the fire (be careful not to touch the flames), you will be able to feel the infrared radiation from the flames warming your hands.

The thermal energy from the burning wood will heat the air around it. The hot air rises up above the fire, as shown by the smoke. Surrounding cold air will be drawn in, forming *convection* currents. The water inside the pan will also heat up by convection.

Car radiator

Combustion engines in petrol-driven cars and motorbikes burn fuel to allow the vehicle to move. During the process, the engine becomes hot and has to be cooled to prevent overheating. One way of doing this is to pump a liquid coolant in metal pipes through the engine and into a radiator. Figure 10.28 explains how thermal energy from the engines is transferred away using a coolant. The arrows represent the movement of the coolant across the engine and the radiator.

1 Metal tubes carry the hot coolant from the engine to the radiator.

2 The radiator contains many thin metal fins. Thermal energy is *conducted* through the metal tube into the fins. The fins have a large surface area, so they are in contact with a lot of air. The fins heat up the air around it, and a fan blows the warmer air away, replacing with cooler air, forming *convection* currents.

3 The tubes and fins are painted black to increase the amount of *infrared radiation* emitted from the hot tubes and fins.

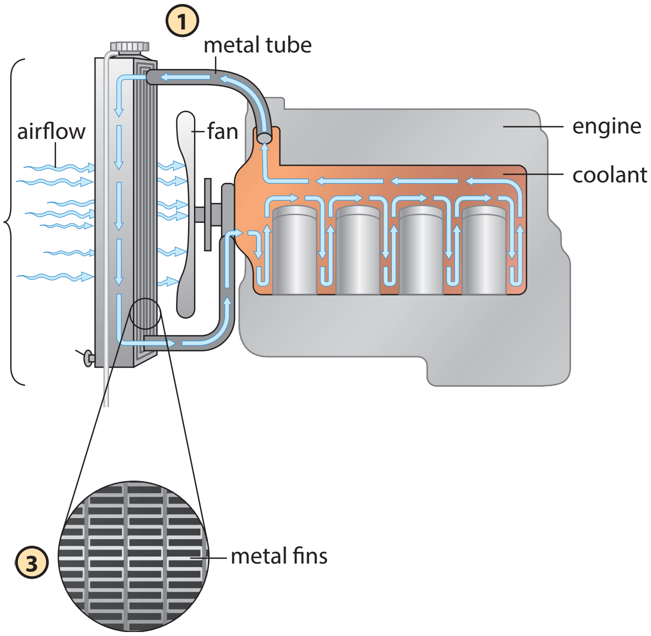


Figure 10.28 Cooling system of a petrol-driven car

Let's Practise 10.5

1 A copper saucepan containing water is placed on a flat electric hot plate.

(a) State the process by which thermal energy is

(i) transferred from the hot plate to the water;

(ii) spread throughout the water.

(b) The sides of the saucepan are well polished. How does this reduce thermal energy loss?

2 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

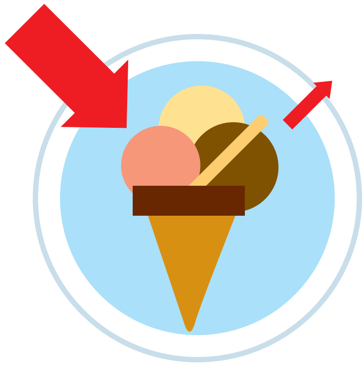
LINK

Exercises 10E–10F, pp. XX–XX

Exercise 10G Let's Reflect, p. XX

Let's Map It

THERMAL ENERGY



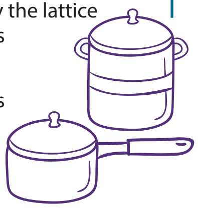
is transferred from

A region of higher temperature to a region of lower temperature until thermal equilibrium is reached.

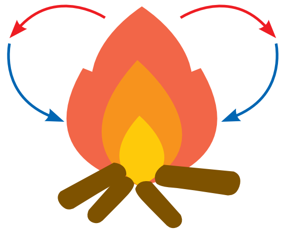
by the processes of

Conduction

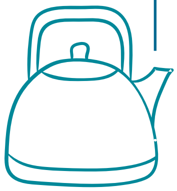
- Through contact between two surfaces
- Requires a medium
- S In non-metals, by the lattice vibration of particles
- S In metals, by the vibration of particles and free electron diffusion



Convection

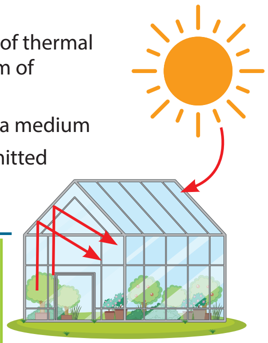


- Through bulk movement of fluids (liquid or gas), forming convection currents
- Requires a medium
- Convection currents form due to changes in the density of the fluid



Radiation

- Through transfer of thermal energy in the form of infrared radiation
- Does not require a medium
- Absorbed and emitted by all objects

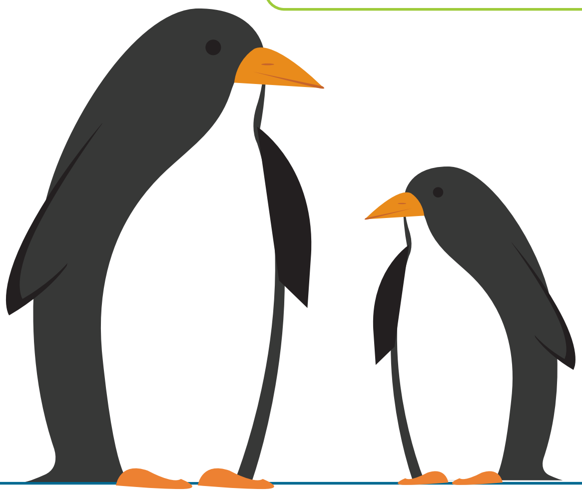


which can be applied in

- Cooking utensils
- Soldering irons
- Double-glazed windows
- Electric kettle
- Air conditioners
- Hot water radiators
- Greenhouse
- S Car radiators

where the rate of thermal energy transfer is affected by

- Surface colour and texture
- S Surface temperature
- S Surface area



Let's Review

Section A: Multiple-choice Questions

1 Ⓢ According to the kinetic theory of matter, thermal energy is transferred from the hot end of a glass rod to the cold end when the molecules from the hot end ______.

- **A** emit infrared radiation to the cold end
- **B** move from place to place so that they collide with the colder molecules and transfer the energy to them
- **C** move to the cold end
- **D** vibrate more vigorously and pass on the energy to the neighbouring molecules

2 In a hot water tank, the heating element should be placed at the bottom because ______.

- **A** conduction cannot take place when the heater is at the top of the tank
- **B** infrared radiation travels faster in the upward direction
- **C** the heated water will rise and this will form convection currents
- **D** the heater must be covered by water at all times

3 Ⓢ In a vacuum flask, the vacuum prevents thermal energy transfer by ______.

- **A** conduction
- **B** conduction and convection
- **C** convection
- **D** radiation

Section B: Short-answer and Structured Questions

1 A cup of hot tea is left on a table. Explain how thermal energy escapes from the tea by

(a) conduction;

(b) convection;

(c) radiation.

2 Explain the following:

(a) A stone floor feels colder to the bare feet than a carpet even though they are at the same temperature.

(b) The freezing compartment is at the top of a refrigerator.

(c) A double-glazed window reduces thermal energy transfer through it.

(d) The hot pipes at the back of a fridge are painted black.

(e) Both the inside and outside of a space blanket are made of a shiny, silvery material.

3 Ⓢ A vacuum flask is used to keep hot liquids hot or cold liquids cold. It is designed to reduce thermal energy from entering or leaving from inside (Figure 10.29).

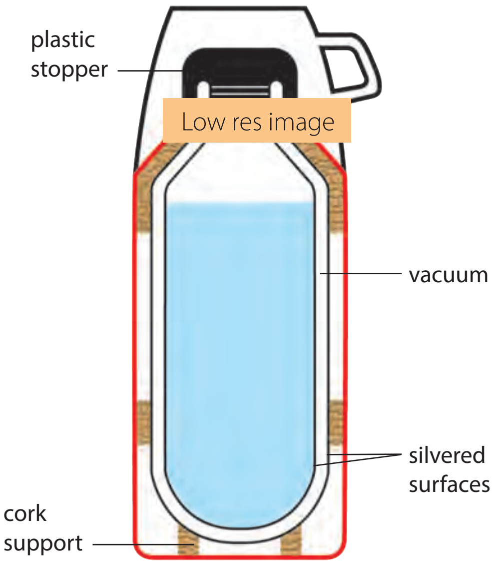


Figure 10.29

Suggest a function of the following parts of the vacuum flask:

(a) The vacuum between the double walls of the glass container

(b) The silvered surfaces of the glass container

(c) The plastic stopper

(d) The cork supports between the inner glass container and outer flask

CHAPTER

11

General Properties of Waves

PHYSICS WATCH

Scan this page to watch a stadium wave in action.

QUESTIONS

- Why can the motion created by the people be described as a wave?
- How could you measure the speed of this wave?
- How is the motion of the people related to the motion of wave?

Have you seen sports fans doing 'the wave' inside a stadium? This wave has many names depending on the location of the stadium. It is popularly known as the Mexican wave after soccer fans in many parts of the world watch it for the first time during the 1986 World Cup in Mexico. Some people call it *la ola*, which means *wave* in Spanish. We can refer to it in general as the stadium wave.

When you find yourself with thousands of people in a major sporting event, have some fun. Start the *la ola*. You don't need water to do it!

11.1 Introducing Waves

In this section, you will learn the following:

- Describe what is meant by a wave motion.
- Know that waves transfer energy without transferring matter.
- Know that for a transverse wave, the direction of vibration is at right angles to the direction of propagation.
- Understand that electromagnetic radiation, water waves and seismic S-waves (secondary) are known as transverse waves
- Know that for a longitudinal wave, the direction of vibration is parallel to the direction of propagation
- Understand that sound waves and seismic P-waves (primary) are known as longitudinal waves

PHYSICS WATCH

Scan this page to watch a clip on wave motion.

When we think of the word *waves*, what often comes to mind is sea waves. Besides sea waves, there are other types of waves, such as sound waves and radio waves. What do all these waves have in common? What are the characteristics of a wave?

What is wave motion?

Wave motion is made up of periodic motion or motion repeated at regular intervals.

For example, the swinging motion of a pendulum bob (Figure 11.1), from the extreme left to the extreme right and back to its starting position, is said to be periodic. One complete cycle of such motion is known as an **oscillation** or a **vibration**. The source of any wave is an oscillation or a vibration.

A wave is a disturbance that *transfers energy* from one place to another. It *does not transfer matter* during the energy transfer (Figure 11.2).

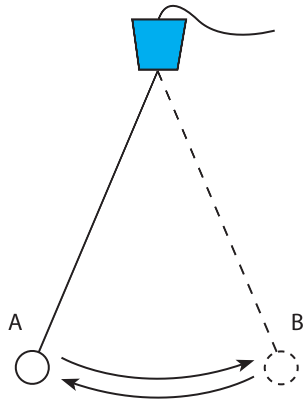


Figure 11.1 *An oscillation is completed when the pendulum bob moves from A to B, and then back to A.*

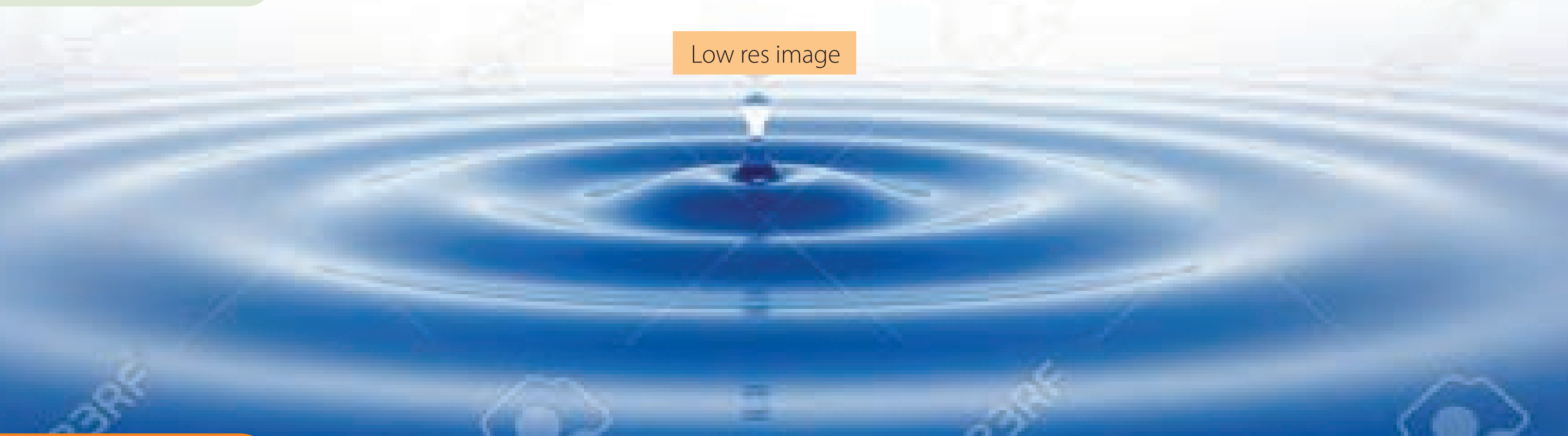
ENRICHMENT INFO

Wave Energy

Have you ever experienced being hit by a huge wave while floating at sea? You would find yourself displaced when you are hit. Work is done by the wave in applying force to move you over some distance.

Thus, the energy carried by waves can be used to do useful work such as generating electricity and pumping water. Wave power has not been utilised as much compared to solar power, wind power and hydropower. However, it is able to generate more power per unit area.

Figure 11.2 *As ripples spread outwards, any object on the water surface (e.g. an empty bottle) will only bob up and down. This shows that waves transfer energy without transferring matter.*

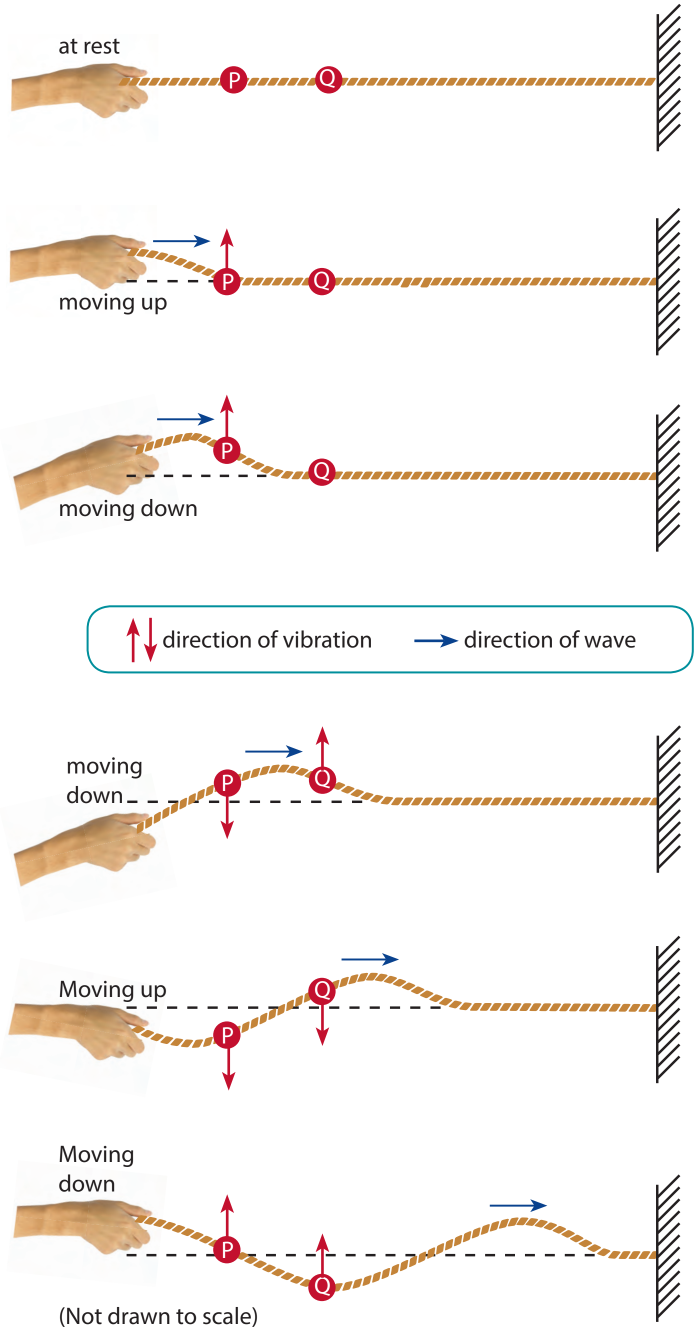


How are waves formed?

We can produce waves using a rope, a ripple tank or a Slinky spring. From each of these cases, we can learn how energy is transferred from one point to another.

Waves in a rope

We can produce waves along a rope by fixing one end of the rope to a wall and moving the other end up and down rapidly (Figure 11.3).



1. One end of the rope is fixed.
2. The kinetic energy (KE) from the moving hand (i.e. source) is transferred to the rope particles (e.g. P) by a rope wave.
3. The rope particles at/near the free end move up and down (i.e. vibrate) as the wave passes through them.
4. The rope wave moves towards the wall.
5. The KE of the rope particles near the source is transferred to rope particles further away (e.g. Q) as the wave progresses.
6. The rope particles further away vibrate up and down.
7. The rope wave continues to move towards the wall.
8. Note that the rope particles vibrate up and down about their rest positions.

Figure 11.3 *The rope particles vibrate in a direction perpendicular to the wave motion.*

Note that the rope waves move towards the wall, while the rope particles only vibrate up and down about their rest positions (Figure 11.3). The energy from the hand is transferred by the rope waves towards the wall. The rope is the medium through which the waves move.

WORD ALERT

Medium: substance, matter

Water waves in a ripple tank

We can use a ripple tank to observe waves. In such a tank, there is a small dipper set near the water surface (Figure 11.4).

① The dipper is set near the water surface.

② The kinetic energy (KE) from the vibrating dipper (i.e. source) is transferred to the water particles directly below it by a circular ripple (i.e. wave).

③ The water particles move up and down (i.e. vibrate) as the ripple passes through them.

④ The circular ripple spreads outwards towards the tank edges.

⑤ The KE gets transferred to the adjacent water particles and eventually to water particles at the tank edges as the ripple progresses.

⑥ The water particles at other parts also vibrate up and down as the ripple passes through them.

⑦ The circular ripple continues to spread outwards towards the tank edges.

⑧ Note that the water particles vibrate up and down about their rest positions.

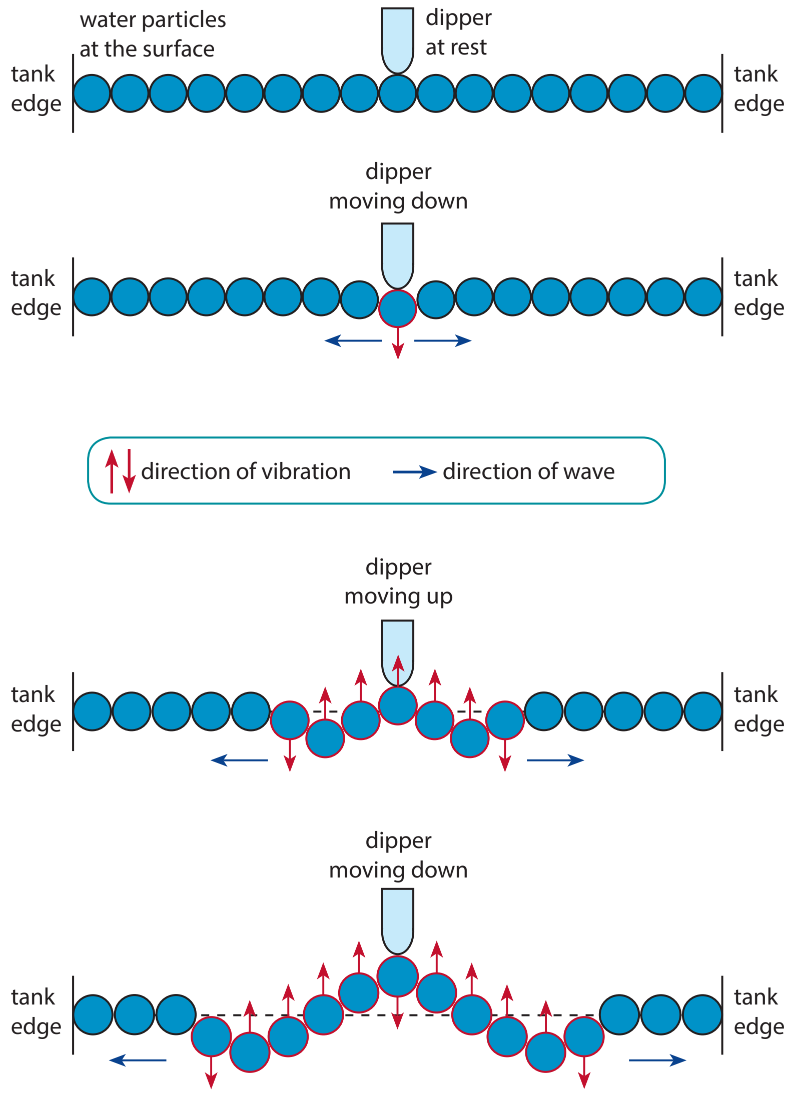


Figure 11.4 *The water particles vibrate in a direction perpendicular to the wave motion*

Note that the circular ripples (i.e. waves) move towards the tank edges, while the water particles only vibrate up and down (Figure 11.5). The energy from the dipper is transferred by the ripples towards the tank edges.

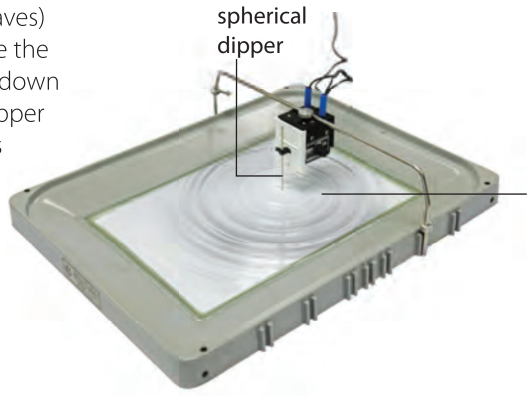


Figure 11.5 *A small dipper in a ripple tank produces circular ripples (waves).*

QUICK CHECK

In Figure 11.5, the medium through which the waves move is air.

True or false?

Waves in a spring

Stretch out a coiled spring or Slinky on the floor and keep one end fixed.

Left-to-right motion

Move the free end of the Slinky left and right (Figure 11.6). Viewing this from the top, we can see the individual coils move perpendicular to the direction of the wave.

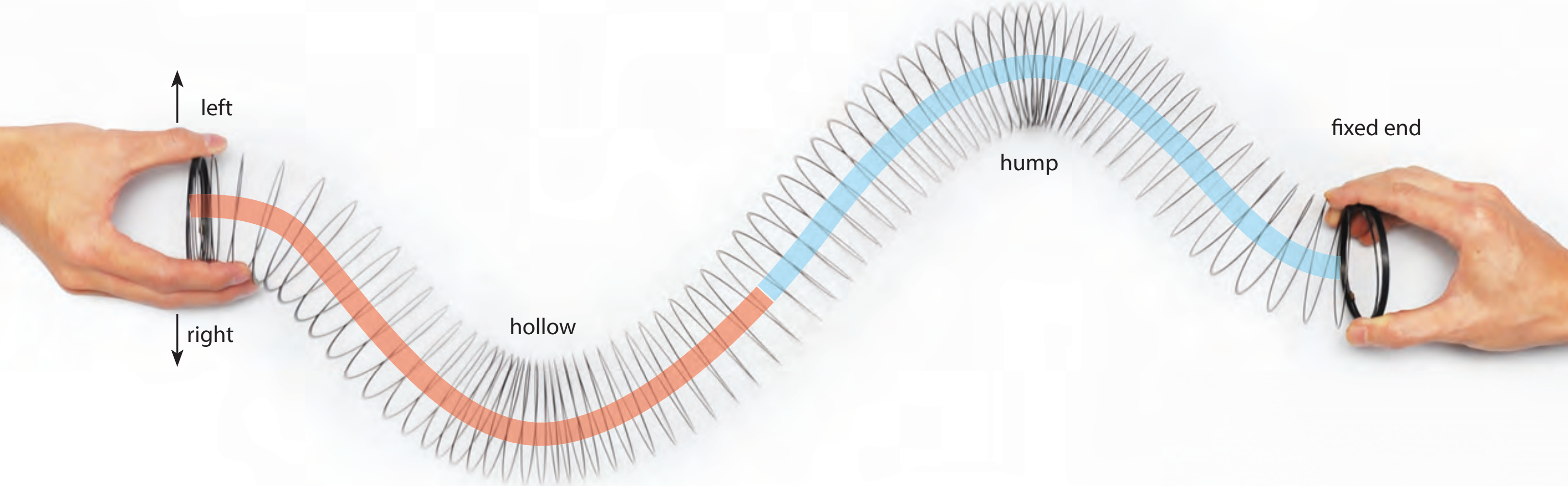


Figure 11.6 *Left-to-right motion of the hand generates waves in a Slinky (top view)*

Push-and-pull motion

Next, push and pull the free end of the Slinky rapidly (Figure 11.7). We can see the individual coils move parallel to the direction of the wave. Dark bands, where the coils are compressed, are seen travelling along the Slinky towards the fixed end.

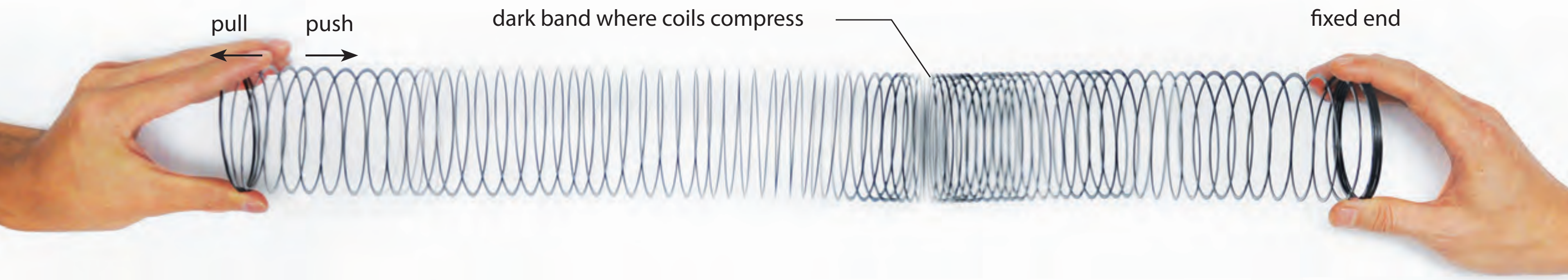


Figure 11.7 *Push-and-pull motion of the hand also generates waves in a Slinky (top view)*

From Figures 11.6 and 11.7, we can observe that the individual coils are restricted to oscillating motion. The individual coils do not move from one end to the other. The waves, however, move from the free end of the Slinky to the fixed end.

As the waves move, energy is transferred from one end of the Slinky to the other. Can you identify the medium in this case?

From our observations of waves produced by the rope, ripple tank and Slinky, we can deduce that waves have the following properties:

- The source of a wave is a vibration or an oscillation.
- Waves transfer energy from one point to another.
- Waves transfer energy without transferring the medium.

WORD ALERT

Propagate: to spread, move or travel through something

LINK

Electromagnetic waves include light waves. You will learn more about light waves in Chapter 12 and electromagnetic waves in Chapter 13.

How many types of wave motion are there?

There are two types of wave motion: transverse and longitudinal waves. We can produce them using a stretched Slinky that is fixed at one end.

Transverse waves

Move the free end of the Slinky up and down repeatedly (Figure 11.8). Do you notice that the up-and-down movement (i.e. vibration) of the individual coils is perpendicular to the wave motion? We call this type of wave a *transverse wave*. Water waves, electromagnetic waves and seismic S-waves (secondary waves) are transverse waves (Figure 11.9).

Transverse waves are waves that propagate perpendicular to the direction of the vibration. We can also say that the direction of the vibration is perpendicular to the direction of propagation.

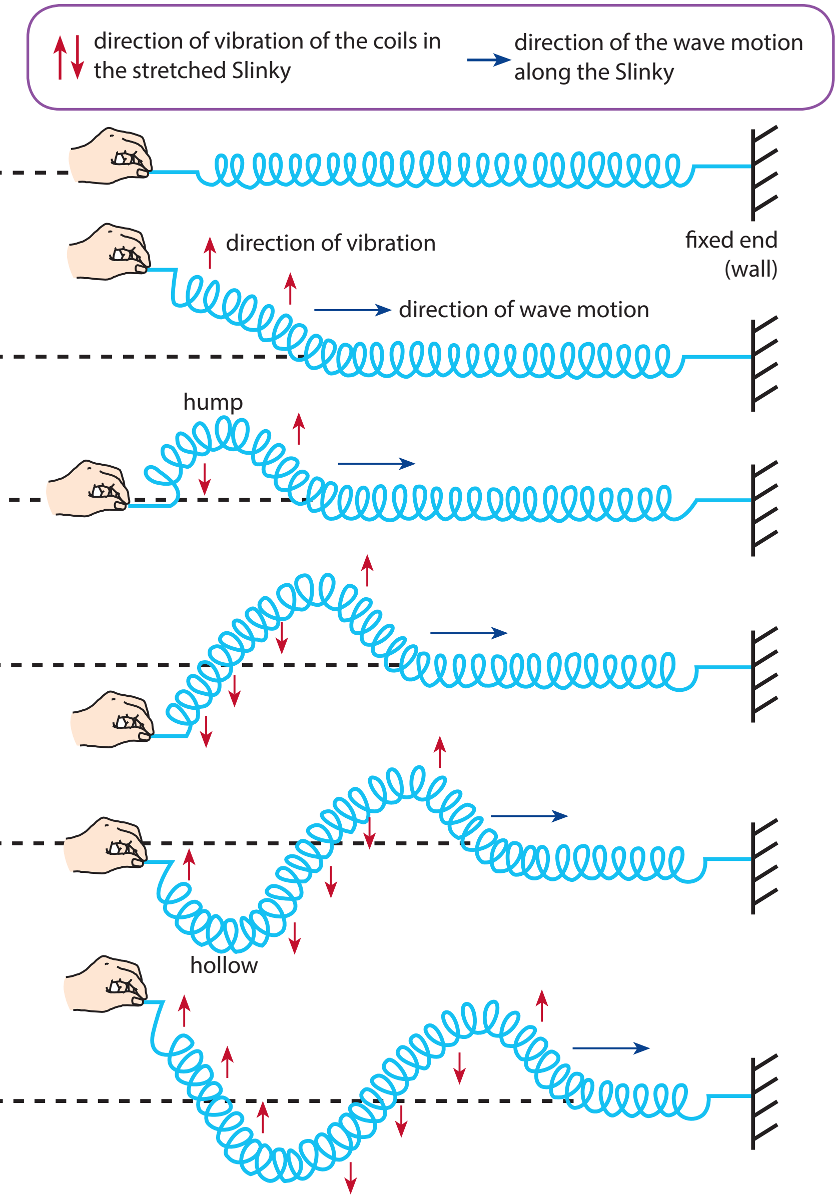
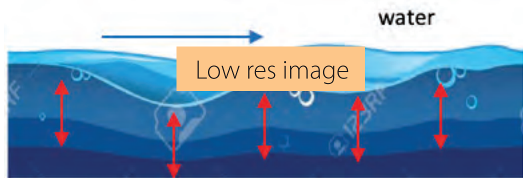
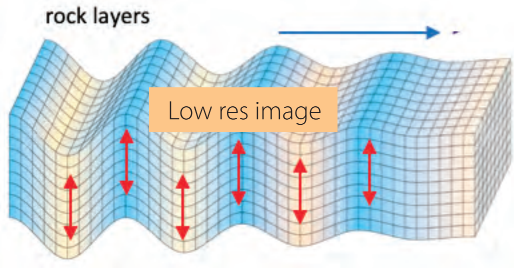


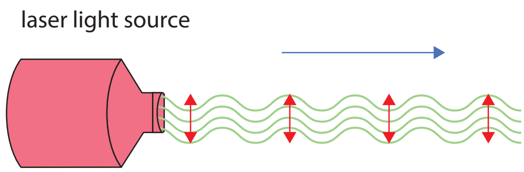
Figure 11.8 For transverse waves, the vibration of the coils (↑↓) is perpendicular to the wave motion (⟶).



Water particles in water waves vibrate up and down as the waves travel horizontally.



An earthquake can cause seismic S-waves to form. The S-waves travel through the Earth as layers of rocks vibrate perpendicularly to the direction of the wave.



Electromagnetic waves such as light waves are produced by charged particles vibrating at right angle to the direction of the wave.

Figure 11.9 These are examples of transverse waves. The red arrows (↕) show the direction of vibration and the blue arrows (⟶) show the wave motion.

PHYSICS WATCH

Scan this page to watch a clip on transverse wave.

Longitudinal waves

Push the free end of the Slinky forward to compress it and pull it backwards to stretch it (Figure 11.10). Do you notice that the forward-and-backward movement (i.e. vibration) of the coils is parallel to the wave motion? This type of wave is called a *longitudinal wave*. Sound waves and seismic P-waves (primary waves) are longitudinal waves (Figure 11.11).

Longitudinal waves are waves that propagate parallel to the direction of the vibration. We can also say that the direction of vibration is parallel to the direction of propagation.

LINK

You will learn more about sound waves in Chapter 14.

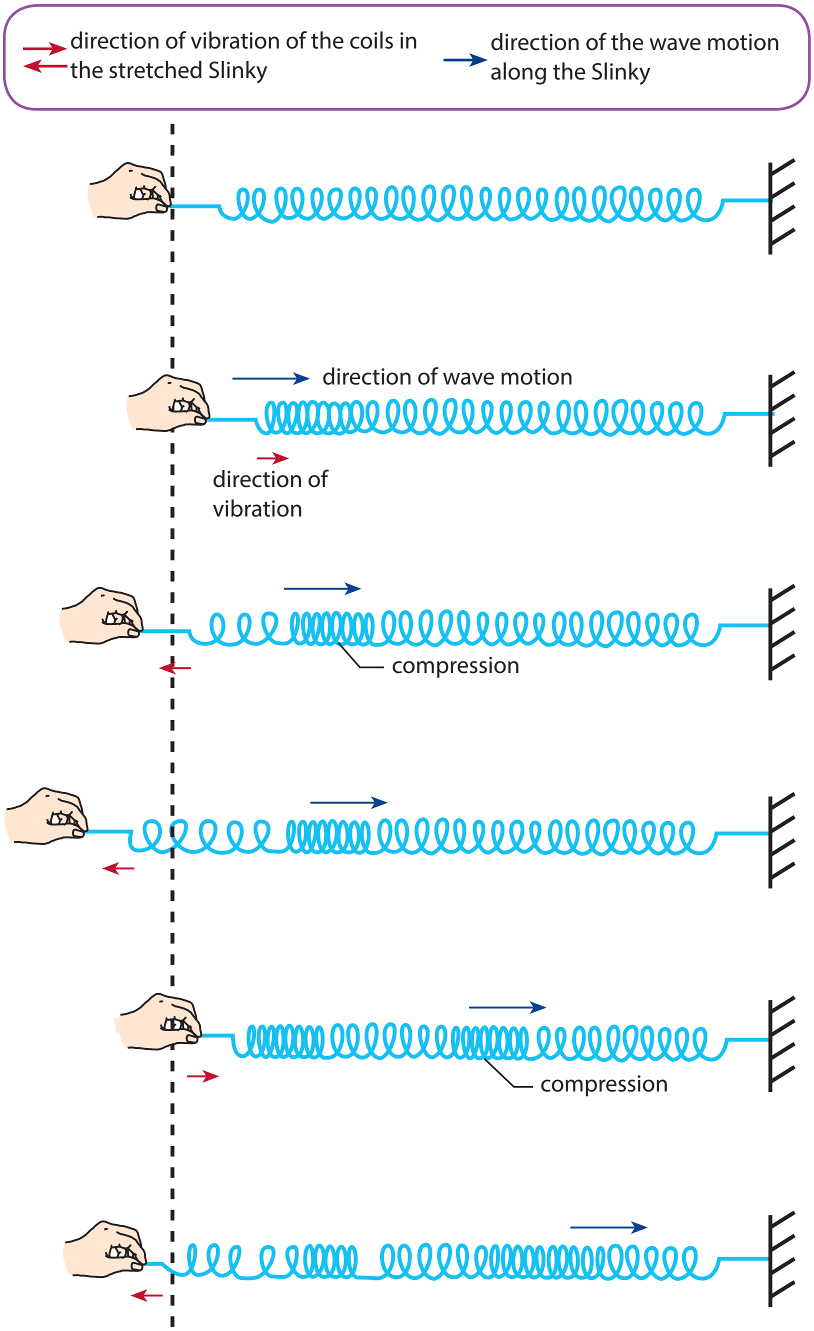
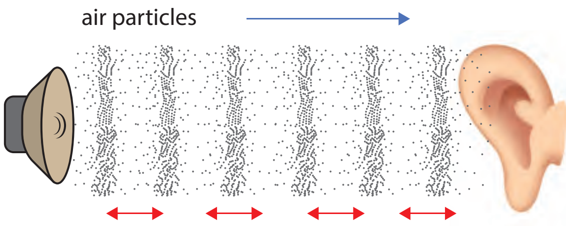
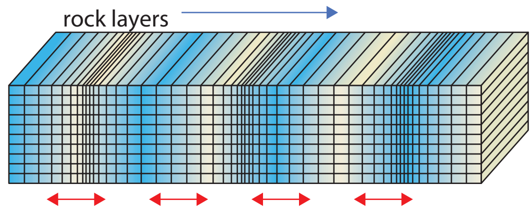


Figure 11.10 *For longitudinal waves, the vibration of the coils (⇄) is parallel to the wave motion (⟶).*



Sound waves are produced by air particles vibrating parallel to the direction of the wave motion.



The seismic P-waves are the first type of waves to be detected during an earthquake. They travel through the Earth as layers of rocks vibrate parallel to the direction of the wave motion.

Figure 11.11 *These are examples of longitudinal waves. The red arrows (⟷) show the direction of vibration and the blue arrows (⟶) show the wave motion.*

QUICK CHECK

For longitudinal waves, the particles do not vibrate along the same direction as the movement of the wave.

True or false?

Let's Practise 11.1

1 State whether each of the statements about rope waves is correct or incorrect.
   (a) Rope waves travel up and down, while the rope moves sideways.
   (b) Rope waves provide a mechanism for the transfer of energy from one point to another.
   (c) Rope waves travel sideways, while the rope moves up and down.

2 (a) State **one** similarity and **one** difference between transverse waves and longitudinal waves.
   (b) Give an example of each type of wave.

3 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB
Exercise 11A, pp. X–X

11.2 Properties of Wave Motion

In this section, you will learn the following:

- Describe the features of a wave.
- Recall and use the equation for wave speed, $v = f\lambda$.

How can we precisely describe waves?

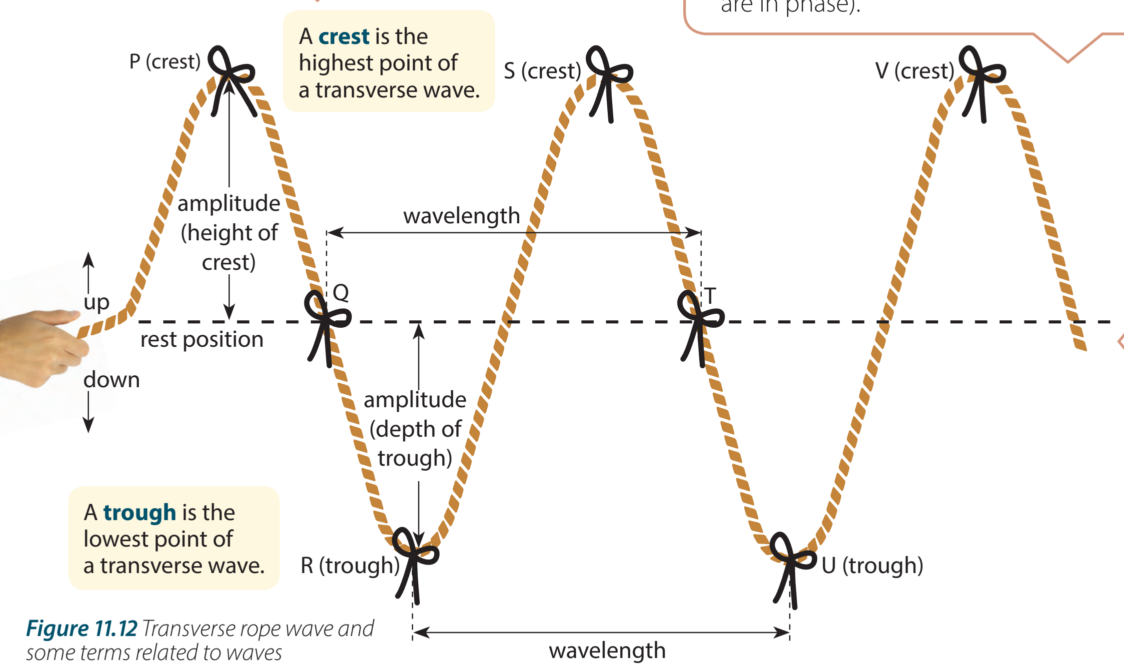
Figure 11.12 shows transverse rope waves that are formed when we move the free end of a rope up and down rapidly. Six ribbons, P, Q, R, S, T and U, are tied at different points along the rope. By observing the movement of these ribbons, we can find out how points along the rope vibrate as the waves move from left to right.

The **amplitude** A of a wave is the maximum displacement of a point from its rest position. Its SI unit is the **metre (m)**.

We can find the amplitude of a transverse wave by measuring the height of its crest or the depth of its trough from the rest position.

Points along a wave are *in phase* if they have the same direction of motion, same speed and same displacement from their rest position. For example,

- P, S and V (i.e. all crests along a wave are in phase);
- R and U (i.e. all troughs along a wave are in phase);
- Q and T (i.e. all alternate points at the rest position along the wave are in phase).



The **wavelength** λ of a wave is the shortest distance between any two points in phase. Its SI unit is the **metre (m)**.

To find the wavelength of a transverse wave, we can measure the distance between

- two successive crests (e.g. P and S, S and V);
- two successive troughs (e.g. R and U);
- any other two nearest points in phase (e.g. Q and T).

Figure 11.12 *Transverse rope wave and some terms related to waves*

Displacement–distance graph

Figure 11.13 shows a displacement–distance graph of the rope wave in Figure 11.12. A photograph of the rope at an instant is equivalent to a displacement–distance graph. A displacement–distance graph describes the displacements of *all particles at a particular point in time*.

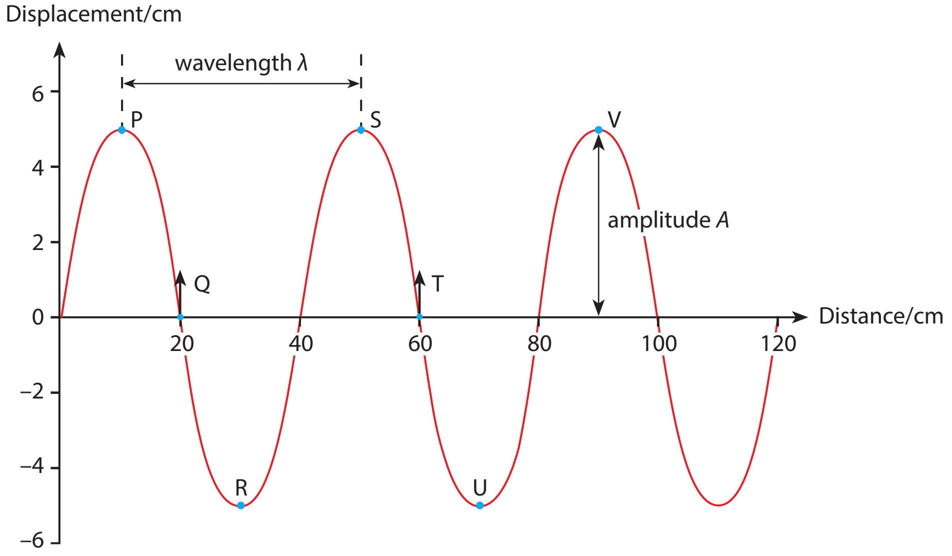


Figure 11.13 *Displacement-distance graph of the rope wave at a certain instant*

Points above the rest position are shown as positive displacements. Points below the rest position are shown as negative displacements.

According to the graph, the amplitude and wavelength of the wave are 5 cm and 40 cm respectively.

Displacement–time graph

Figure 11.14 shows the displacement–distance graphs captured at different instants during the flicking of the rope in Figure 11.12.

By tracking the displacements of ribbon Q and plotting them against time, we obtain the displacement–time graph of Q over one second (Figure 11.15). A displacement–time graph describes the displacement of *one particle over a time interval*.

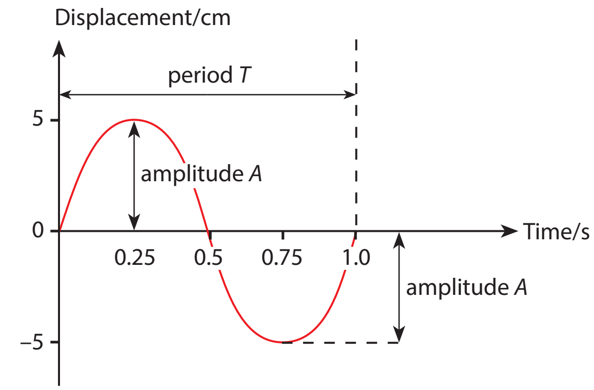


Figure 11.15 *Displacement-time graph of Q over one second*

According to the graph, the amplitude and the period of the wave are 5 cm and 1.0 s respectively.

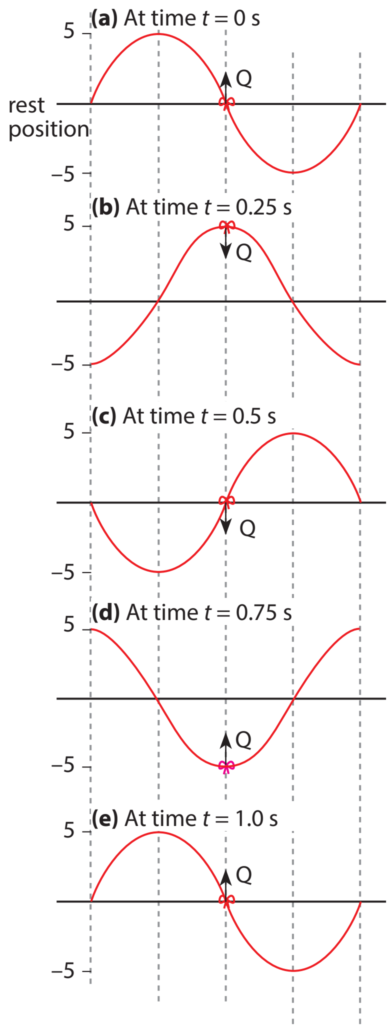


Figure 11.14 *Displacement-distance graphs at different instants over one second*

The **period** T of a wave is the time taken to produce one complete wave. Its SI unit is the **second (s)**.

The period is equivalent to the time taken for the wave to travel through a distance equal to its wavelength.

The **frequency** f of a wave is the number of complete waves produced per second. Its SI unit is the **hertz (Hz)**.

The frequency of a wave is also the number of crests (or troughs) that go past a point per second.

In Figure 11.15 on page 169, one complete wave is produced per second — the frequency of the wave is 1.0 Hz. We can relate frequency to period by the equation $f = \frac{1}{T}$. The higher the frequency, the greater the number of waves produced in one second. A higher frequency also implies that the period is shorter.

Since a crest (or any point on a wave) travels a distance of one wavelength in one period, the wave speed is given by:

$v = \frac{\lambda}{T}$ where v = wave speed (in m/s)
λ = wavelength (in m)
T = period (in s)

Since $f = \frac{1}{T}$,

$$\boldsymbol{v = f\lambda}$$

Wave speed v is the distance travelled by a wave per second. Its SI unit is the **metre per second (m/s)**.

A wavefront can be drawn by joining all the adjacent wave crests. Depending on how the waves are produced, the wavefronts can be straight lines (Figure 11.16), concentric circles (Figure 11.17), or any other shape.

A **wavefront** is an imaginary line on a wave that joins all adjacent points that are in phase.

QUICK CHECK

A dipper is moved up and down to produce waves in water. Increasing the frequency of the dipper will increase the speed of the waves.

True or false?

QUICK CHECK

Refer to pages 168 to 169. The speed of the wave shown in Figures 11.12 to 11.15 is 0.4 cm/s.

True or false?

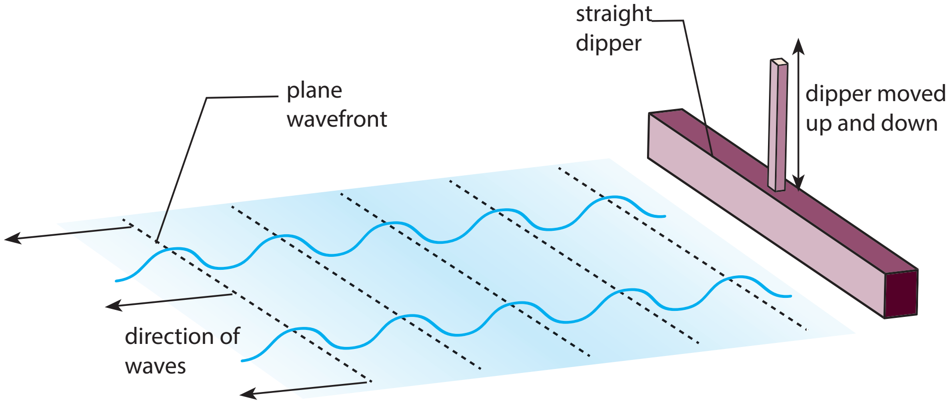


Figure 11.16 *A straight dipper produces plane waves that give rise to plane wavefronts.*

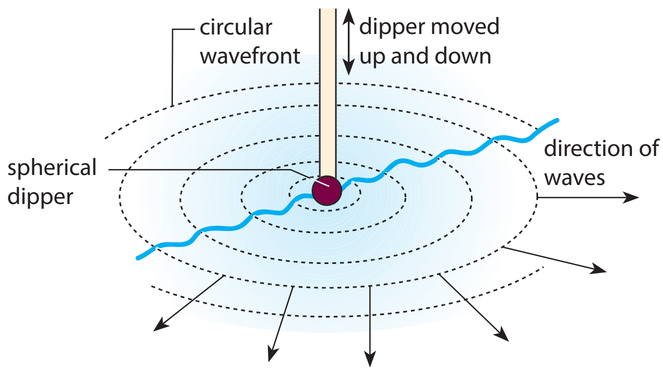


Figure 11.17 *A spherical dipper produces circular waves that give rise to circular wavefronts.*

Worked Example 11A

Figure 11.18 shows a displacement–distance graph of a wave.

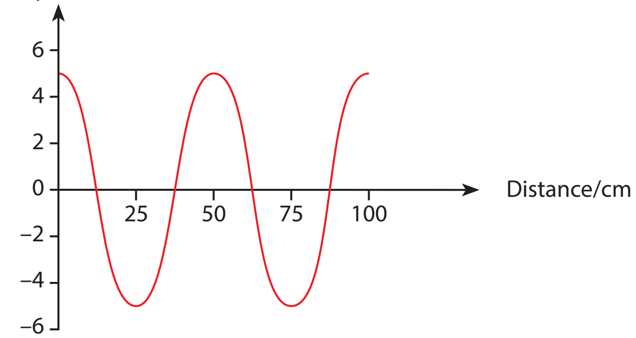


Figure 11.18

(a) What is the wavelength of the wave?

(b) The period of the wave is 1.0 s. What are its frequency and speed?

(c) What will be the wavelength of the wave if its frequency is increased to 5.0 Hz, with no change in speed? Sketch the resulting wave profile with its wavelength marked clearly.

Solution

(a) Wavelength $\lambda = 50$ cm

(b) Given: Period $T = 1.0$ s

Frequency $f = \frac{1}{T}$

$= 1.0$ Hz

Using the wave speed equation,

Wave speed v = frequency $f \times$ wavelength λ

$= 1.0 \text{ Hz} \times 50 \text{ cm}$

$= 50$ cm/s

(c) Given: Wave speed $v = 50$ cm/s

Frequency $f = 5.0$ Hz

Using the wave speed equation,

$v = f\lambda$

$\lambda = \frac{v}{f} = \frac{50 \text{ cm/s}}{50 \text{ Hz}} = 10 \text{ cm}$

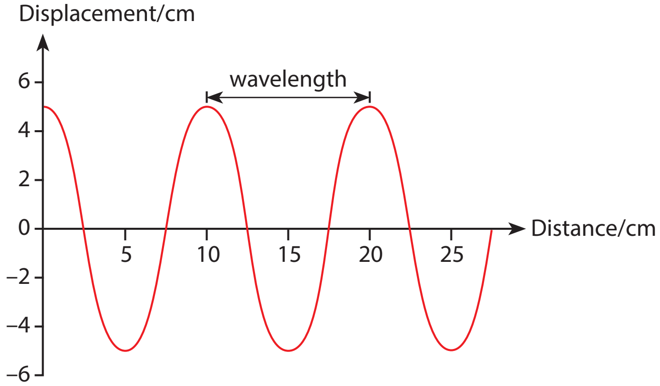


Figure 11.19

Worked Example 11B

(a) Figure 11.20 shows a wave along a Slinky with a frequency of 3 Hz and a wavelength of 0.3 m. What is the wave speed?

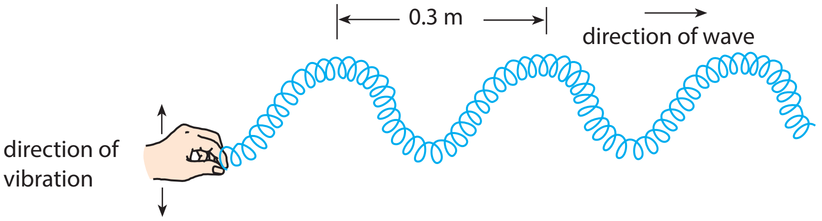


Figure 11.20

(b) Given that in a vacuum, the speed c and wavelength λ of green light are 3.0×10^8 m/s and 0.6 µm respectively, calculate the frequency of the green light.

(c) Compare the waves in **(a)** and **(b)** and comment on them, in terms of speed and frequency.

Solution

(a) Given: Frequency $f = 3$ Hz

Wavelength $\lambda = 0.3$ m

Using $v = f\lambda$,

$v = 3 \text{ Hz} \times 0.3 \text{ m} = 0.9$ m/s

(b) Given: Wavelength $\lambda = 0.6 \text{ µm} = 0.6 \times 10^{-6}$ m

Speed $c = 3.0 \times 10^8$ m/s

Using $c = f\lambda$, where f is the unknown frequency of the green light:

$$f = \frac{c}{\lambda}$$

$$= \frac{3.0 \times 10^8 \text{ m/s}}{0.6 \times 10^{-6} \text{ m}} = 5.0 \times 10^{14} \text{ Hz}$$

(c) The speed and frequency of green light are much greater than the speed and frequency of the waves in the Slinky.

LINK PWB
Practical 11A, pp. XX–XX

Let's Practise 11.2

1. Figure 11.21 shows the displacement–time graph of a periodic motion. Determine the
   (a) period; **(b)** frequency; **(c)** amplitude?
2. State the relationship between the speed, frequency and wavelength of a wave.
3. A wave has an amplitude of 0.4 m and a wavelength of 10.0 m. It is travelling at a speed of 5.0 m/s. Sketch a graph to show how the displacement of a particular point on the wave changes with time. Label the amplitude and period on the graph clearly.
4. **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

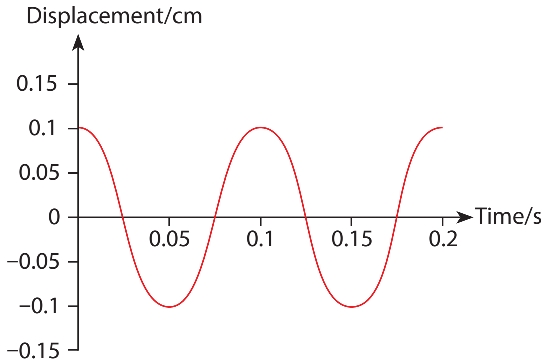


Figure 11.21

LINK TWB
Exercise 11B, pp. X–X

11.3 Common Features of Wave Behaviour

In this section, you will learn the following:

- Describe how waves can undergo reflection, refraction and diffraction.
- Describe the use of a ripple tank to show reflection, refraction and diffraction of waves.
- S Describe how wavelength and gap size affects diffraction through a gap.
- S Describe how wavelength affects diffraction at an edge.

How do the wavefronts relate to the direction of travel of the waves? The ripple tank can be used to show how water waves behave differently in different situations. Note that in all the wave diagrams in this section, all wavefronts are at 90° to the direction of propagation of the wave. For clarity, the ripple tank itself is not shown.

LINK

Most of these wave behavior are looked at in the context of light in Chapter 12.

What happens when waves hit a straight barrier?

A straight edge is used to create ripples with plane wavefronts. A straight barrier with a plane surface is inserted into the water. When the water waves hit the barrier, they undergo **reflection**. The waves bounce off the plane surface without changing shape.

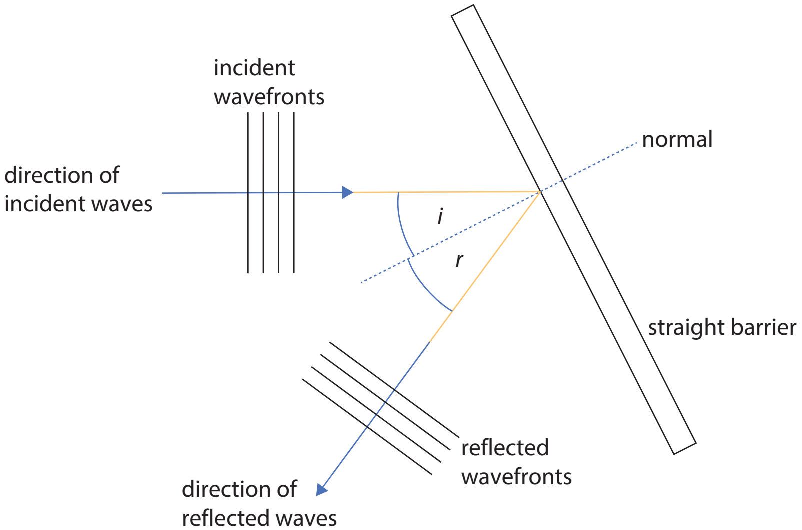


Figure 11.22 Reflection of water waves in a ripple tank

HELPFUL NOTES

The distance between two adjacent wavefronts is equivalent to the wavelength. Notice in Figure 11.22 that this distance remains the same before and after reflection. This means that the wavelength does not change.

Figure 11.22 shows how the water waves hit the barrier at an angle *i* and get reflected at an angle *r*. Notice that both angles are equal. This is similar to light waves hitting a plane mirror and sound waves hitting a wall.

LINK

You will learn more about light and sound reflection in Chapters 12 and 14 respectively.

WORD ALERT

Boundary: frontier where two areas meet

What happens when waves pass from one medium to another?

A translucent plate is placed inside a ripple tank so that a portion of the water is deep and another portion is shallow. Figure 11.23 shows plane water waves travelling from the deep water to the shallow water. The wave is said to have crossed the boundary between the deep and shallow water.

Notice the wavefronts in the shallow water are closer together than those in the deep water. This shows that the waves travel faster in the deep water. Given that $v = f\lambda$ and that the frequency is constant, this means that when the waves are in the shallow water, their wavelength must also decrease.

It is also observed that the waves undergo **refraction** when the they pass from one medium to another. In Figure 11.23, we see the waves change direction or bend when they cross the boundary between the deep and shallow waters at an angle. If the angle i is zero, angle r will also be zero, i.e., no refraction occurs.

QUICK CHECK

If the waves are travelling slower in the shallower water, then they must also have a smaller amplitude.

True or false?

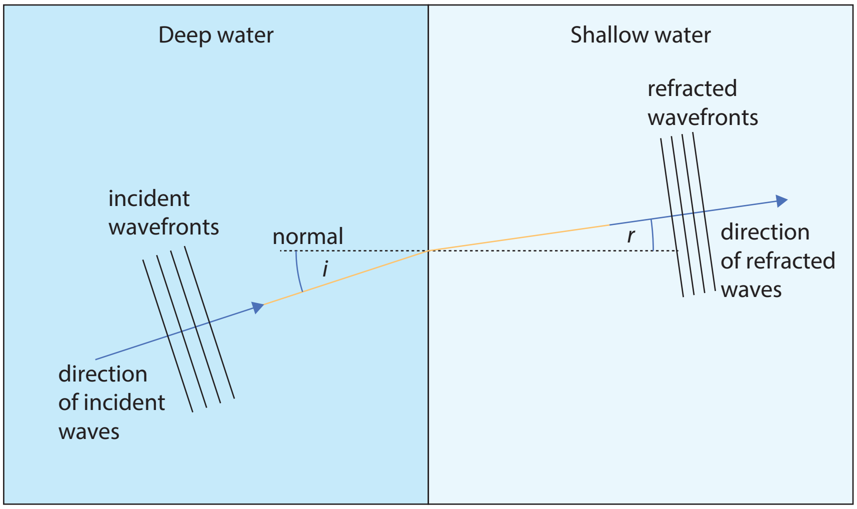
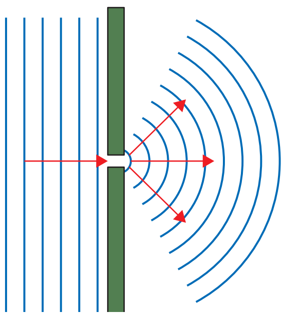


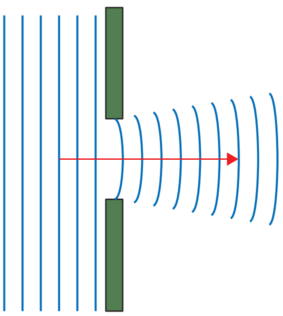
Figure 11.23 *Refraction of water waves in a ripple tank*

What happens when waves encounter a gap or an edge?

Small barriers are placed inside a ripple tank to create gaps of different widths through which plane water waves can pass. Notice that the wavefronts spread out after passing through the gaps (Figure 11.24). This is called *diffraction*.



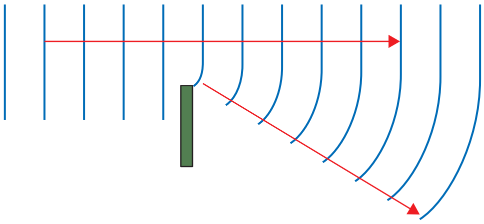
(a) Waves entering a narrow gap



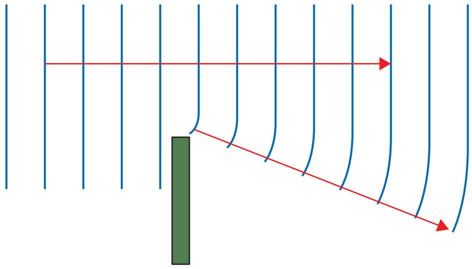
(b) Waves entering a wide gap

Figure 11.24 *Diffraction of water waves arriving at gaps of different widths*

Place a barrier inside a ripple tank to let plane water waves pass over one edge of the barrier. In this case diffraction still occurs. The waves appear to curve around and spread behind the barrier (Figure 11.25).



(a) Long wavelength



(b) Short wavelength

Figure 11.25 *Diffraction of water waves arriving at a single edge*

In summary, **diffraction** involves the spreading out of waves when they encounter gaps and edges.

S How does gap size and wavelength affect diffraction? As gap size increases relative to the wavelength, the **curvature** at the ends of the wavefronts becomes smaller.

Compare the two diagrams in Figure 11.24. When the wavelength is longer than the gap size, the waves spread out more (Figure 11.24(a)). When the wavelength is shorter than the gap size, the waves spread out less (Figure 11.24(b)). The wavefronts are mostly unchanged and only affected at the ends.

How does wavelength affect diffraction at an edge? This time, the longer the wavelength, the greater the curvature effect. This means a greater proportion of the wave will curve around and spread behind the barrier (Figure 11.25).

Let's Practise 11.3

1 Figure 11.26 shows some concrete sea barriers and an area of beach at the sea shore.

(a) The water waves have carved out near semi-circular areas from the sand. Suggest how straight plane water waves have done this.

(b) The gaps between the barriers are approximately 20 m wide. Suggest possible values for the wavelength of the waves.

(c) S Explain how the patterns in the sand would be different if

(i) the wavelength of the water waves was shorter;

(ii) the gaps were wider.

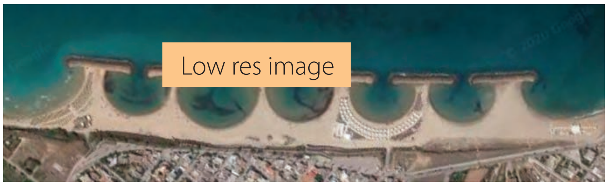


Figure 11.26 *Beach area with sea barriers*

2 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

WORD ALERT

Curvature: curved or rounded shape

ENRICHMENT
THINK

A house is located at the foot of a hill on the opposite side of a transmitter. The transmitter emits both TV and radio signals.

Explain why it is more difficult to receive TV signals in the house compared to radio signals.

LINK

Exercise 11C–11D, pp. XX–XX

Exercise 11E Let's Reflect. p. XX

Let's Map It

WAVES

Transfer energy without transferring matter

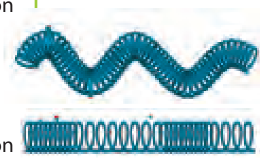
Wave motion is made up of periodic motion or motion repeated at regular intervals.

Transverse wave

- Direction of vibration is perpendicular to direction of propagation

Longitudinal wave

- Direction of vibration is parallel to direction of propagation



Wave behaviour

Refle tion

- Waves bounce off the plane surface without changing shape.

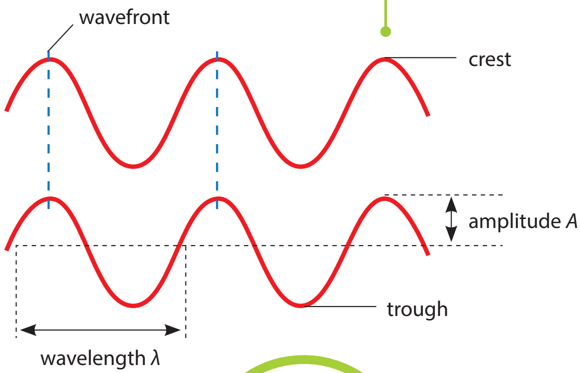
Refraction

- Waves change direction when pass from one medium to another; usually accompanied by a change in speed of the waves.

Diff action

- Waves spread out when they encounter gaps and edges.

Wave features



Can be plotted on a

- displacement–distance graph
- displacement–time graph

Frequency f is the number of complete waves produced per second.

Period T is the time taken to produce one complete wave.

Wave speed is the distance travelled by a wave per second and given by:

$$v = f\lambda$$

Let's Review

Section A: Multiple-choice Questions

1 What does a wave transfer?

A Molecules B Energy
C Matter D Force

2 As a transverse wave passes, the particles of the medium oscillate

A in phase with one another.
B with different frequencies.
C parallel to the direction of the wave travel.
D perpendicular to the direction of travel of wave.

3 Which of the following is an example of longitudinal waves?

A Waves in a ripple tank
B Light waves in air
C A vibrating guitar string
D Sound waves produced by a vibrating guitar string

4 Figure 11.27 shows the displacement–time graph of a particle in a transverse wave. If its speed is 2 cm/s, which of the following pairs of amplitude and wavelength is correct?

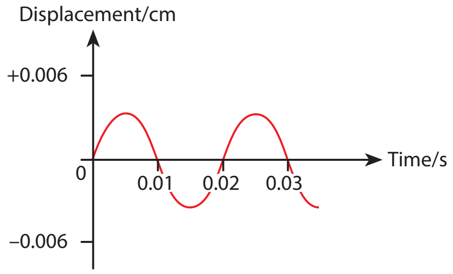


Figure 11.27

	Amplitude/cm	Wavelength/cm
A	0.02	0.006
B	0.003	0.02
C	0.003	0.04
D	0.006	0.04

5 A vibrating dipper of frequency 3 Hz produces water waves in a ripple tank. Which of the following is a possible wavelength and speed of the waves?

	Wavelength/cm	Speed/cm/s
A	3	1
B	3	6
C	4	12
D	15	5

6 From the sea to the shore, the depth of the water decreases. Which of these statements describes waves coming in from the sea to the shore?

A Speed increases and amplitude decreases.
B Speed increases and amplitude increases.
C Speed decreases and amplitude increases.
D Speed decreases and amplitude decreases.

7 S A beam of light was shone through a gap. Diffraction of light was not observed. What does this suggest about the wave nature of light?

A Light is not a wave.
B The speed of light is very large.
C The wavelength of visible light is much larger than the width of the gap.
D The wavelength of visible light is much smaller than the width of the gap.

Section B: Short-answer and Structured Questions

1 **(a)** What is meant by *a frequency of 2 Hz*?

(b) **(i)** Draw a labelled diagram to show the waveform in a rope with a wavelength of 5 cm and an amplitude of 3 cm.

(ii) Assuming the rope wave is travelling from left to right at a speed of 0.50 m/s, calculate the frequency of the wave.

2 Water waves enter a dock at a rate of 120 crests per minute. At the dock are two poles 12 m apart. A worker watches a particular wave crest pass from one pole to another in 4 s. Calculate the

(a) frequency of the wave motion;
(b) wavelength of the waves.

Let's Review

3 Draw the displacement–distance graphs for the following waveforms:
  (a) Two waves that have the same amplitude and speed, but one has a frequency that is twice that of the other
  (b) Two waves that have the same speed and frequency, but one has an amplitude that is twice that of the other

4 Figure 11.28 shows the instantaneous position of some particles in a medium through which waves are passing continuously in the direction indicated by the arrow.

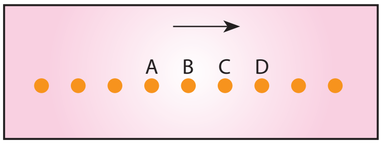


Figure 11.28

Describe the motion of the particles A, B, C and D if the wave is
  (a) longitudinal;
  (b) transverse.

5 Figure 11.29 shows a displacement–distance graph and a displacement–time graph of a wave.

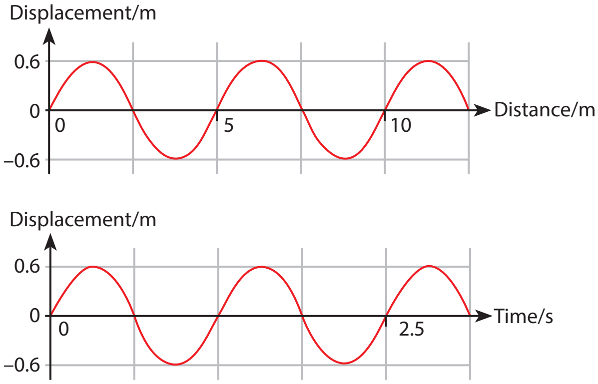


Figure 11.29

  (a) State the amplitude of the wave.
  (b) State the wavelength of the wave.
    (i) State the time taken for one complete oscillation.
    (ii) Calculate the frequency of the wave.
    (iii) Calculate the speed of the wave.

6 Figure 11.30 shows water waves about to encounter deeper water. Complete the diagram to show qualitatively the path and wavelength of the waves in the deeper water.

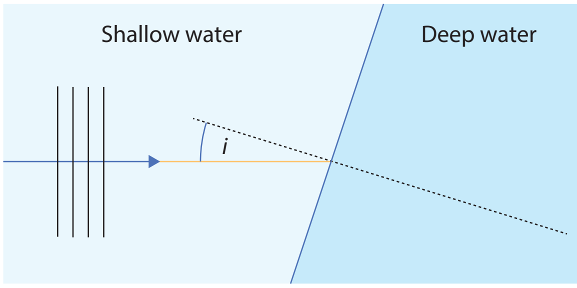
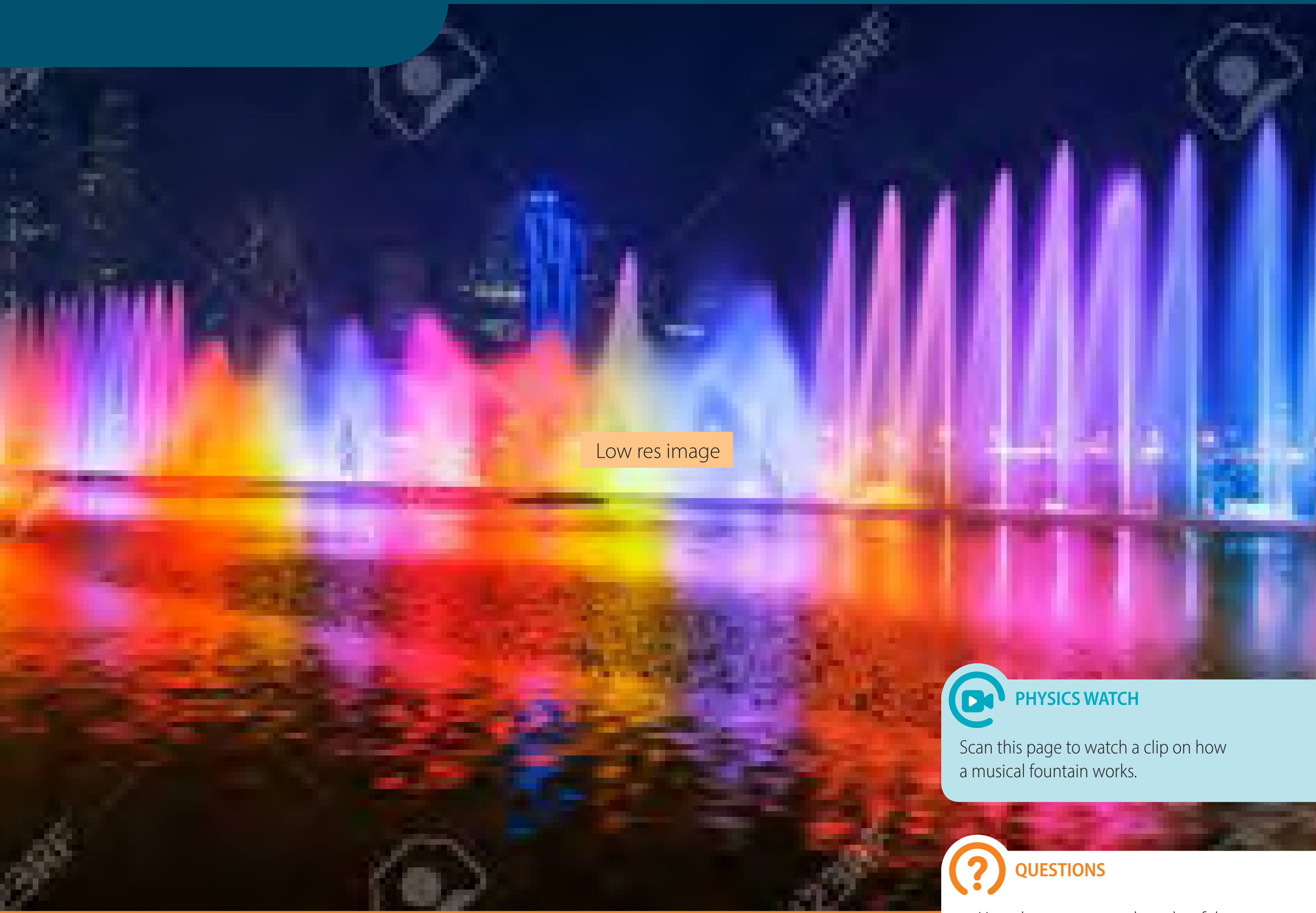


Figure 11.30

7 S Explain how a conversation in a corridor can be heard around a corner in the corridor.

CHAPTER

12 Light



PHYSICS WATCH

Scan this page to watch a clip on how a musical fountain works.

QUESTIONS

- How do our eyes see the colourful musical fountain?
- How do the colours get into the water?
- How does the light and water interact?

Have you ever seen a musical fountain?

There is one in Sharjah, in the United Arabs Emirates. The Sharjah Musical Fountain, as shown in the photo, is one of the biggest and most spectacular in the region. Many people enjoy watching how the fountain dances with the music. What is more interesting is the colourful jets of water. The elegant and complex fountain uses the interaction between light and water to create the stunning effects.

Don't just enjoy the show — get to know the science behind it!

12.1 Reflection of Light

In this section, you will learn the following:

- Define and use the terms *normal*, *angle of incidence* and *angle of reflection*.
- Describe the formation of an optical image by a plane mirror, and give the characteristics of the image.
- State that for reflection, the angle of incidence is equal to the angle of reflection; recall and use this relationship.
- S Use simple constructions, measurements and calculations for reflection by plane mirrors.

How do we represent light?

You have learnt that light is a form of electromagnetic wave. The wave nature of light enables it to undergo reflection. This explains how we see things. We can see objects around us only if light from them enters our eyes. Luminous objects, such as a lamp or a fire, can be seen because they give out their own light. Non-luminous objects, such as a wall picture, are visible to us because they reflect light from a light source into our eyes (Figure 12.1).

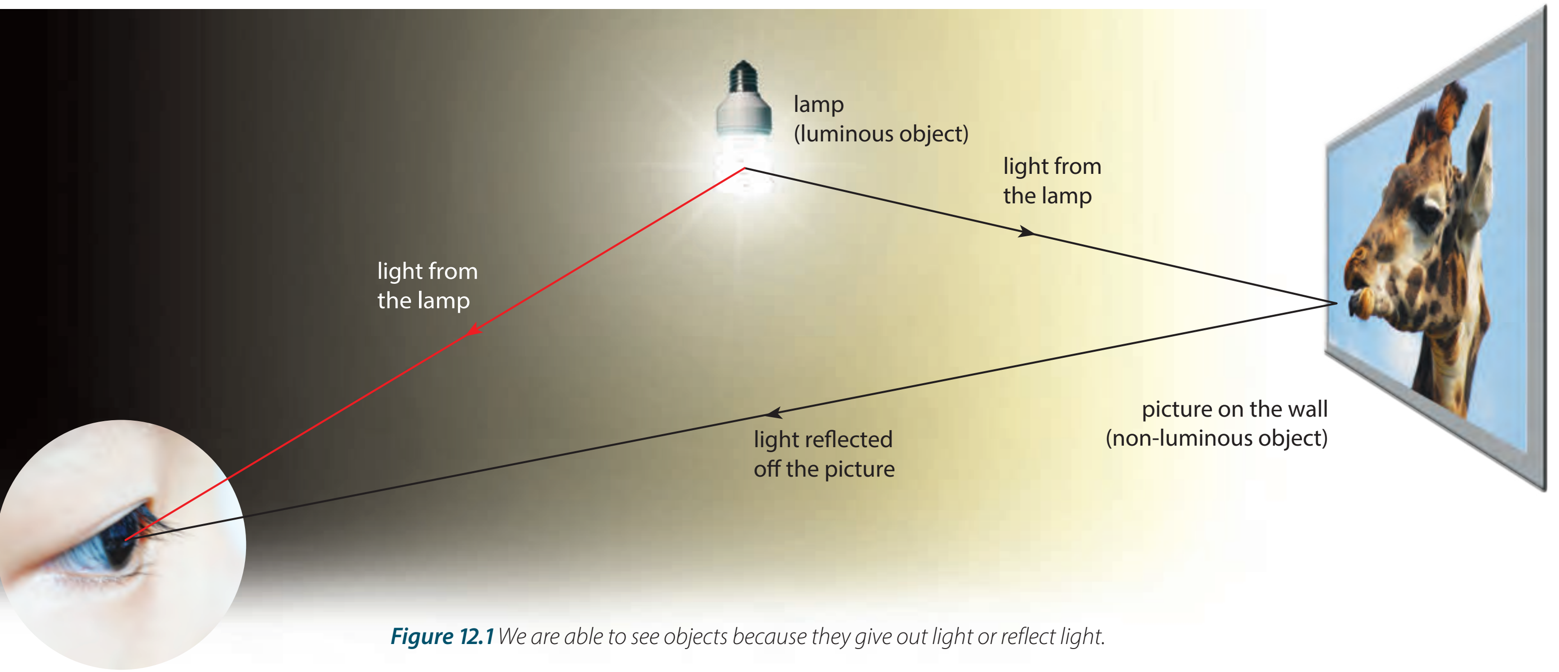
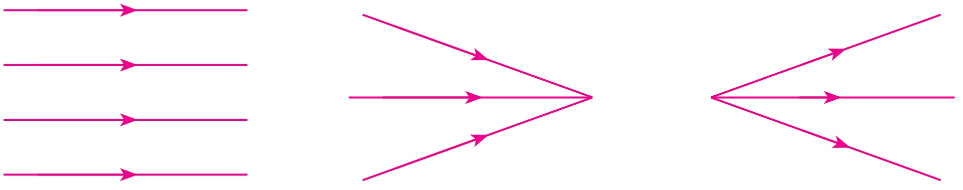


Figure 12.1 *We are able to see objects because they give out light or reflect light.*

In physics, we use straight lines with arrows to represent paths of light. The arrows indicate the direction in which the light travels. Such lines are called light rays. A beam of light is actually a bundle of light rays.

A light beam can be a bundle of parallel rays, convergent rays or divergent rays (Figure 12.2). We use parallel lines to represent light rays from a distant object (e.g. the Sun), and divergent lines to represent light rays from a nearby object.



▲ Parallel light rays ▲ Convergent light rays ▲ Divergent light rays

Figure 12.2 *Different types of light rays*

Below are some terms that are used to describe the reflection of light:

- **Reflection** is the rebounding of light at a surface.
- **Incident ray** is light ray that hits the reflecting surface.
- **Point of incidence** is the point at which the incident ray hits the reflecting surface.
- **Reflected ray** is light ray that bounces off the reflecting surface.

Can you identify the incident ray, point of incidence and reflected ray in Figure 12.1?

What is the law of reflection?

We can carry out Let's Investigate 12A to learn about the law that governs the reflection of light.

Let's Investigate 12A

Objective
To investigate the law of reflection

Apparatus
Plane mirror, ray box and power supply, paper

Precautions
A ray box with a filament lamp may get hot.

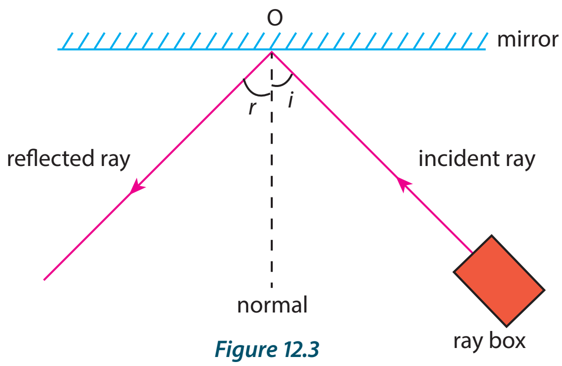


Figure 12.3

Procedure

1. Figure 12.3 shows the reflection of light by a plane mirror. Note that the mirror needs to be placed vertically upright (i.e. at right angle to the sheet of paper).
2. Mark out a dotted line perpendicular to the mirror on the paper. This line is the called the *normal*.
3. Label the intersection of the mirror and the normal, 'O'.
4. Switch on the ray box and direct a ray of light at point O.
5. Measure and record the angle of incidence *i* and the corresponding angle of reflection *r*.
6. Repeat steps 4 and 5 for different angles of incidence *i*.

Results and discussion

1. Every angle of incidence *i* is equal to its corresponding angle of reflection *r*.
2. The incident ray, reflected ray and the normal at the point of incidence all lie in the same plane (i.e. a flat surface).

Our finding from Let's Investigate 12A is consistent with the **law of reflection**:

- the angle of incidence *i* is equal to the angle of reflection *r* (i.e. $i = r$).

Below is a summary of a few more terms you need to know for reflection of light:

- **Normal** is the imaginary line perpendicular to the reflecting surface at the point of incidence.
- **Angle of incidence** *i* is the angle between the incident ray and the normal.
- **Angle of reflection** *r* is the angle between the reflected ray and the normal.

LINK

Recall the reflection of waves that you have learnt in Chapter 11.

LINK

Practical 12A, pp. XX–XX

ENRICHMENT *THINK*

Explain why the shoes (Figure 12.4) shine after they have been polished.

Figure 12.4 *Polished shoes*

Worked Example 12A

Figure 12.5 shows a ray of light incident on a mirror.

(a) State the relationship between the angle of incidence and the angle of reflection.

(b) Complete the diagram to show the reflected ray.

(c) What is the angle of incidence?

(d) What is the angle of reflection?

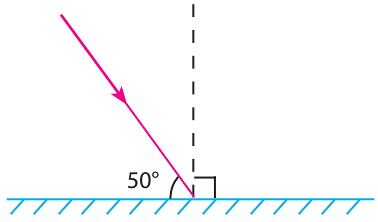


Figure 12.5

Solution

(a) The angle of incidence is equal to the angle of reflection.

(b) Refer to Figure 12.6.

(c) Angle of incidence $i = 90° - 50° = 40°$

(d) Based on the law of reflection, angle of reflection $r = i = 40°$.

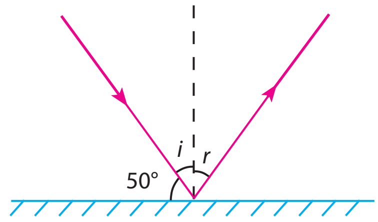


Figure 12.6

What are the properties of a mirror image?

We can carry out Let's Investigate 12B to learn the characteristics of an image formed in a plane mirror.

Let's Investigate 12B

Objective

To investigate the characteristics of an image formed in a plane mirror

Apparatus

Plane mirror, three pins, graph paper, wooden holder, softboard

Precautions

The pins are sharp.

Procedure

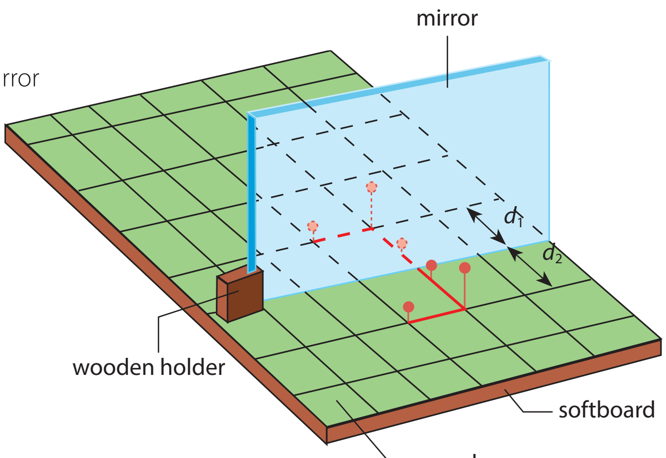


Figure 12.7

1 Set up the apparatus shown in Figure 12.7.

2 Observe the images formed.

3 Find the distances d_1 and d_2 by counting the number of squares between one of the pins and the mirror surface, and between its image and the mirror surface. Compare these two distances.

4 Repeat step 3 for the two other pins and their images.

Observations

The following observations were made regarding the mirror images.

1 The image of each pin is the same size as the pin, upright and virtual.

2 The distances of the image from the plane mirror, d_1, is equal to the distance of the object form the plane mirror, d_2.

3 Taking the figure formed by the pins as an object, its image is laterally inverted.

LINK PWB
Practical 12B, pp. XX–XX

Characteristics of a plane mirror image

From Let's Investigate 12B, we can conclude the following characteristics of a plane mirror image:

- The image is of the **same size** as the object.
- The image is **laterally inverted**. The left-hand side of the image appears as the right-hand side of the object and vice versa.
- The image is **upright**.
- The image is **virtual**. It cannot be captured on a screen and the light rays do not meet at the image position. This is opposite to a real image.
- The image has the **same distance** from the mirror as the object.

Note: A **real** image can be captured on a screen and the light rays meet at the image position.

Worked Example 12B

(a) There are seven letters in the word PHYSICS.

(i) Hold the word up in front of a plane mirror as shown in Figure 12.8. Write down how these letters appear in the mirror.

(ii) How many of these letters appear to be different when the word is reflected?

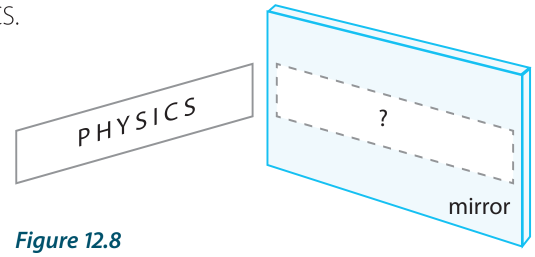


Figure 12.8

(iii) Write down the letters that appear to be the same.

(b) The driver of car A saw car B behind him from his rear-view mirror. If the registration number of car B is SDE 789H, write down the number, as seen by the driver of car A in his rear-view mirror.

Solution

(a) (i) Ƨ Ɔ I Ƨ Y H ꟼ

(ii) 4 **(iii)** H, Y, I

(b) Hɘ8ᒣ ƎᗡƧ

Ray diagrams for plane mirrors

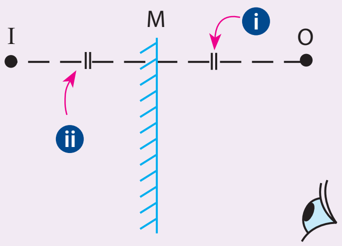
We cannot capture a mirror image on a screen because it is a virtual image. However, we can locate its position by drawing ray diagrams. Figure 12.9 shows a point object O in front of a plane mirror M. The point object O is represented by a dot. The mirror is represented by a straight line, with shading to show its silvered back.

Figure 12.9

Ray diagram for a point object

Figure 12.10 shows how a ray diagram for a point object is drawn.

Step 1
Locate the position of the image I behind the mirror.

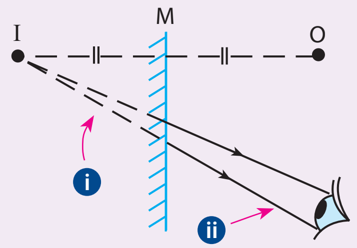


distance of mirror image behind mirror = distance of object in front of mirror

i Measure the perpendicular distance from object O to the mirror surface.

ii Mark off the same distance behind the mirror to locate the image I.

Step 2
Draw the reflected rays.

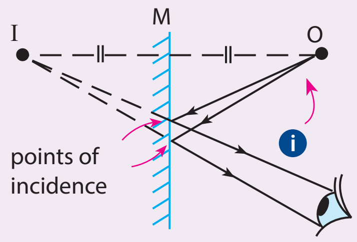


Join the image I to the eye using straight lines.

i Draw dotted lines for the rays behind the mirror.

ii Draw solid lines with arrowheads for rays reflected off the mirror. The arrowheads indicate the direction that light is travelling in.

Step 3
Draw the incident rays.



i Join the object O to the points of incidence on the mirror surface. Note that, for each ray, the angle of incidence is equal to the angle of reflection.

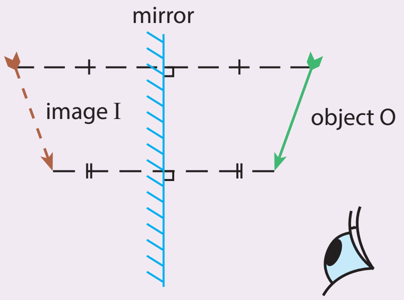
Figure 12.10 Drawing a ray diagram for a point object

By measuring the distances IM and OM, it can be seen that the distance from the object to the mirror and the mirror to the image are the same.

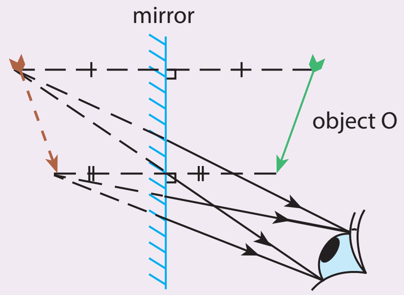
Ray diagram for an extended object

An extended object can be seen as many points. To draw the ray diagram for the extended object (Figure 12.11), we need to select several of these points and apply the same steps in Figure 12.10 to them.

Step 1
Locate the position of the image I behind the mirror using the two extreme points.



Step 2
Draw the reflected rays from the selected points.



Step 3
Draw the incident rays to the points of incidence.

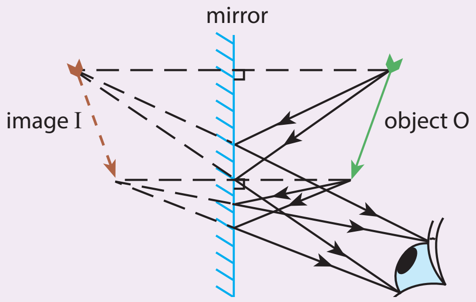


Figure 12.11 Drawing a ray diagram for an extended object

By measuring the length of the image and the length of the object, it can be seen that the size of the image and the size of the object are the same.

Worked Example 12C

Two point objects P and Q are placed at different positions in front of a plane mirror, as shown in Figure 12.12.

(a) Draw a single ray to locate the position of the image of P as seen by the eye at E.

(b) The eye at E is also able to see the image of Q. Draw a single ray to show how this is possible.

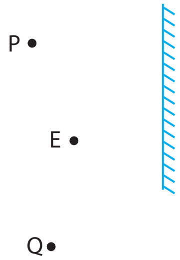


Figure 12.12

Solution

Refer to Figure 12.13.

(a) P' is the image of P.

(b) Q' is the image of Q.

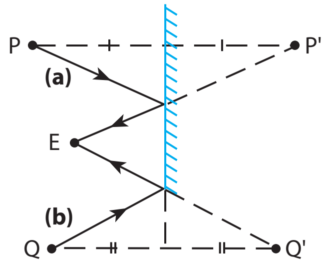


Figure 12.13

WORD ALERT

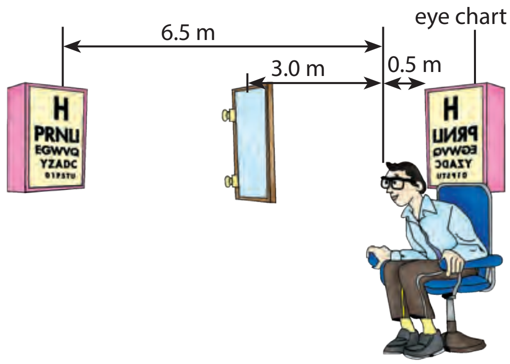
Optical: relating to sight or the ability to see

Some applications of mirrors

Figure 12.14 shows some applications of mirrors.

Vision testing

Before you can get a pair of spectacles at an optical shop, you have to go through a vision test. You need to read letters and numbers off an eye chart from a standard distance during the test. To allow a vision test to be carried out in a small room, mirrors are used to make the numbers on the eye chart appear further away.



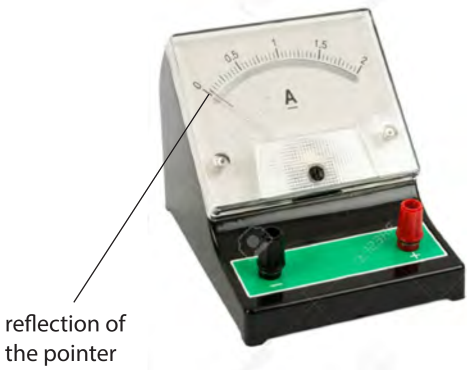
Applications of mirrors

Periscope

A periscope comes with two plane mirrors inclined at 45°. It helps a person look over obstacles such as a high wall or other spectators in a game or an event!

Blind corner mirror

Fitting curved mirrors at the corners of shops allows shopkeepers to keep a lookout for shoplifters. Such mirrors are also used to help drivers see around blind corners before making a turn.



Instrument scale

A mirror placed below the pointer of a scale can help us avoid parallax error when taking readings. To avoid parallax error, we need to make sure that the pointer is aligned with its mirror image.

Figure 12.14 *Applications of mirrors*

Let's Practise 12.1

1 With the help of a diagram, state the law of reflection.
2 What are the characteristics of an image formed in a plane mirror?
3 **S** Figure 12.15 shows an arrow placed above a mirror.
   (a) On the diagram,
      (i) draw its image formed by the mirror;
      (ii) show how light rays from the object are reflected at the mirror to form the image for the eye.
   (b) Describe the image.

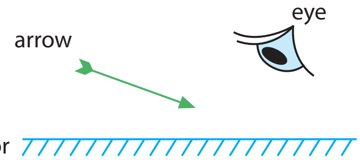


Figure 12.15

4 **S** A person is looking at the image of an eye chart in a mirror placed 3.0 m in front of him. Given that the actual eye chart is positioned 0.5 m behind his eyes, find the distance between the image of the chart and his eyes.
5 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

Exercise 12A, pp. XX–XX

12.2 Refraction of Light

In this section, you will learn the following:

- Define and use the terms *normal*, *angle of incidence* and *angle of refraction*.
- Describe an experiment to show refraction of light.
- Describe the passage of light from one medium to another through a transparent material.
- **S** Define *refractive index*, *n*.
- **S** Recall and use the equation $n = \dfrac{\sin i}{\sin r}$.

LINK

Recall the refraction of waves that you have learnt in Chapter 11.

Light can travel through transparent materials such as glass and water. This is why we can see a pencil in a glass of water. But why does the pencil appear bent at the water surface (Figure 12.16)?

Light travels at different speeds in different transparent materials (i.e. optical **media**). For example, its speed is 3.0×10^8 m/s in air and 2.0×10^8 m/s in glass. When light travels from air to glass, it undergoes a change in speed at the **boundary** of the two optical media. The change in speed causes light to bend (i.e. change its direction). This called *refraction*.

WORD ALERT A-Z

Media: (plural of medium), matter, substances

Boundary: interface where two areas meet

Figure 12.16 *We can see the pencil in a glass of water because it reflects light through the water and glass into our eyes. But why does the pencil appear bent?*

Light travels the fastest in vacuum. It slows down in an optically denser medium (e.g. glass, water). Figure 12.17 shows a ray of light striking and refracting at a surface, PQ.

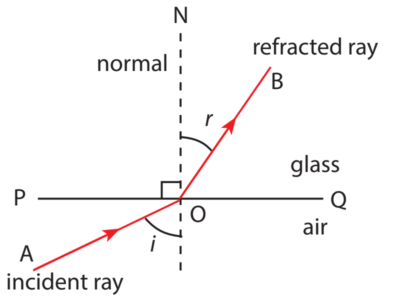


Figure 12.17 *Refraction of light at a surface*

Below are some terms that are used to describe the refraction of light:

- **Refraction** is the bending of light as it passes from one optical medium to another.
- **Incident ray** is light ray that hits the refracting surface.
- **Point of incidence** is the point at which the incident ray hits the refracting surface.
- **Normal** is the imaginary line perpendicular to the refracting surface at the point of incidence.
- **Angle of incidence** *i* is the angle between the incident ray and the normal.
- **Angle of refraction** *r* is the angle between the refracted ray and the normal.

What is the law of refraction?

We can carry out Let's Investigate 12C to learn the law that governs the refraction of light.

Let's Investigate 12C

Objective
To investigate the law of refraction

Apparatus
Translucent rectangular block, ray box and power supply, paper

Precautions
A ray box with a filament lamp may get hot.

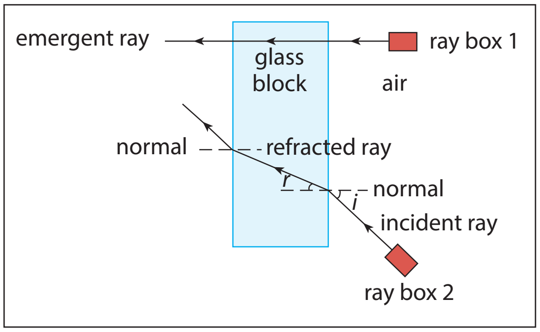


Figure 12.18 *a piece of paper*

Procedure

1 Place the glass block on a piece of paper.
2 Using ray box 1, shine a light ray through the glass block along the normal (Figure 12.18), and observe the path of the light ray.
3 Using ray box 2, shine a light ray through the glass block at an angle (Figure 12.18), and observe the path of the light ray.
4 Vary the angle of incidence *i* and measure the corresponding angles of refraction *r*. Tabulate the results as shown in Table 12.1 and plot the graph of sin *i* against sin *r* as shown in Figure 12.19.

Table 12.1 *Recorded data and calculated values*

i / °	r / °	$\sin i$	$\sin r$	$\frac{\sin i}{\sin r}$
20.0	13.0	0.342	0.225	1.52
30.0	20.0	0.500	0.342	1.46
40.0	25.0	0.643	0.423	1.52
50.0	31.0	0.766	0.515	1.49
60.0	35.0	0.866	0.574	1.51
70.0	39.0	0.940	0.629	1.49

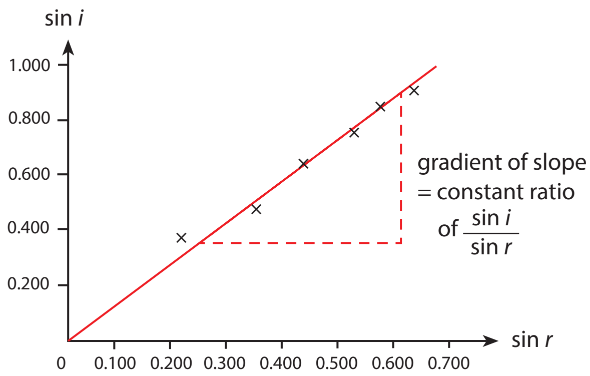


Figure 12.19

LINK PWB

Practicals 12C–12D, pp. XX–XX

WORD ALERT

Conversely: on the other hand, in the opposite way

HELPFUL NOTES

Although a light ray travelling from one medium to another along the normal is not refracted, it still undergoes a change in speed.

Observations and results

1 For ray box 1, the light ray passes through the glass block in a straight line. There is no change in its direction.

2 For ray box 2,
- the light ray bends towards the normal as it enters the block;
- the light ray bends away from the normal as exits the block. The emergent ray is parallel to the incident ray;
- S the graph of sin *i* against sin *r* is a straight line the goes through the origin with a constant gradient (Figure 12.19).

Discussion and conclusion

1 A light ray that travels from one medium to another along the normal is not refracted.

2 A light ray bends towards the normal when it enters an optically denser medium at an angle (e.g. air to glass).

3 Conversely, a light ray bends away from the normal when it enters an optically less dense medium at an angle (e.g. glass to air).

4 The incident ray, the normal and the refracted ray all lie in the same plane.

5 S From Figure 12.19, we can deduce that the ratio of sin *i* to sin *r* for a particular medium (or gradient of its straight-line graph) gives us a constant.

S The conclusion in Let's Investigate 12C is consistent with the **law of refraction** discovered by the Dutch scientist, Willebrord Snell:

- For two given media, the ratio of the sine of the angle of incidence, *i*, to the sine of the angle of refraction, *r* is a constant.

  $$\frac{\sin i}{\sin r} = \text{constant}$$

  This is also known as **Snell's Law**.

Refractive index and speed of light

The **refractive index** *n* is the ratio of the speeds of a wave in two different regions.

Consider light travelling through a medium. The refractive index *n* of a medium is the ratio of the speed of light in vacuum to the speed of light in the medium.

$n = \frac{c}{v}$ where c = speed of light in vacuum

v = speed of light in the medium

The higher the value of the refractive index of a medium, the slower light travels in the medium.

For light travelling from vacuum to an optical medium, the constant ratio $\frac{\sin i}{\sin r}$ is also known as the refractive index *n* of that medium.

$\boldsymbol{n = \frac{\sin i}{\sin r}}$ where i = angle of incidence in vacuum

r = angle of refraction in the medium

The higher the value of the refractive index of a medium, the smaller the angle of refraction *r* (i.e. the more the light bends towards the normal). This is can be seen when we compare refraction in diamond to refraction in water (Figure 12.21).

QUICK CHECK

In Figure 12.20, medium P is optically more dense than medium Q.

True or false?

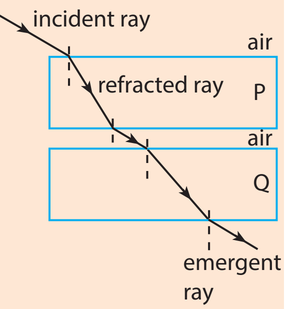


Figure 12.20

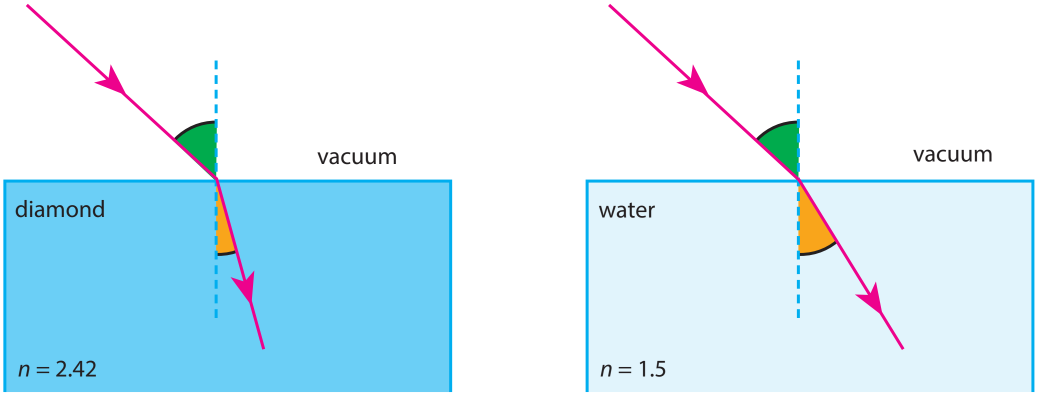


Figure 12.21 *The angle of refraction is smaller in diamond than in water*

Table 12.2 *Refractive indices of and speed of light in some materials*

Medium	Refractive index *n*	Speed of light ($\times 10^8$ m/s)
Diamond	2.40	1.25
Glass	1.50*	2.00
Perspex	1.50	2.00
Water	1.33	2.25
Ice	1.30	2.30
Air	1.000 293	2.999

* For glass, the refractive index varies between 1.48 and 1.96, depending on the composition of the glass.

From Table 12.2, we can see that the speed of light in air is very close to that in vacuum. Hence, for most practical purposes, we can find the approximate value of the refractive index even though we use the speed of light in air instead of vacuum.

$$n = \frac{\text{speed of light in vacuum}}{\text{speed of light in medium}} \approx \frac{\text{speed of light in air}}{\text{speed of light in medium}}$$

Worked Example 12D

Given that the speed of light in vacuum is 3.0×10^8 m/s, calculate the speed of light in crown glass of refractive index 1.52.

Solution

Given: Speed of light in vacuum $c = 3.0 \times 10^8$ m/s
Refractive index of crown glass $n = 1.52$

Using $n = \frac{c}{v}$ where v = speed of light in crown glass,

$$v = \frac{c}{n}$$
$$= \frac{3.0 \times 10^8 \text{ m/s}}{1.52}$$
$$= 1.97 \times 10^8 \text{ m/s}$$

WORD ALERT

Indices: plural of *index*

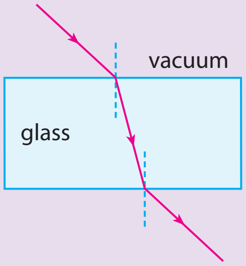
HELPFUL NOTES

A transparent material of higher refractive index is an optically denser medium.

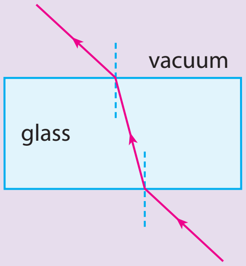
However, optical density is different from mass density. For example, liquid paraffin is optically denser than water, but its mass density is lower.

HELPFUL NOTES

A light ray will travel along the same path if its direction of travel is reversed (Figure 12.23). This is the *principle of reversibility* and it applies to the reflection and refraction of light.



(a) When light shines from top to bottom



(b) When the direction of light is reversed, the angles it makes with the normal are the same as in (a).

Figure 12.23

Worked Example 12E

Figure 12.22 shows a ray of light passing through a rectangular glass block of refractive index 1.5.

If the ray strikes the surface PQ at an angle of incidence i of 60°, calculate the

(a) angle of refraction r at the air-to-glass boundary (PQ);

(b) angle of incidence x in the glass block;

(c) angle of refraction y at the glass-to-air boundary (RS).

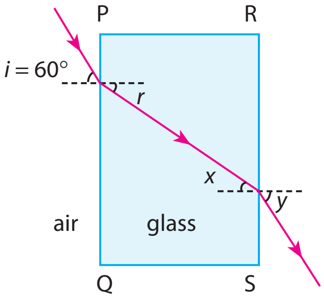


Figure 12.22

Solution

Given: Refractive index of the glass $n = 1.5$

(a) At the air-to-glass boundary (PQ):

$$n = \frac{\sin i}{\sin r} \text{ (Snell's law)}$$

$$\sin r = \frac{\sin i}{n} = \frac{\sin 60°}{1.5}$$

$$r = 35.3°$$

(b) Since x and r are alternate angles, $x = r = 35.3°$

(c) At the glass-to-air boundary (RS):

In this case, we cannot write $n = \frac{\sin x}{\sin y}$ as the angle of incidence x is not in air. However, since a light ray travels along the same path if its direction is reversed, we can solve for angle of refraction y by reversing the direction of the light ray.

$$n = \frac{\sin x}{\sin y} \text{ (Snell's law)}$$

$$\sin y = n \sin x = 1.5 \sin 35.3°$$

$$y = 60°$$

Worked Example 12F

Figure 12.24 shows a ray of light being partially reflected and refracted at the surface of a glass block of refractive index 1.6.

Determine the value of

(a) x; **(b)** y.

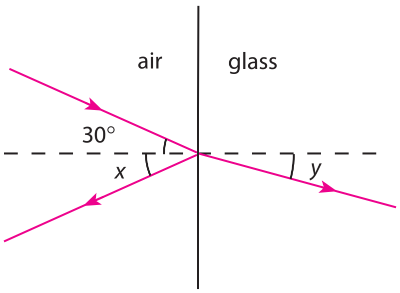


Figure 12.24

Solution

Given: Angle of incidence = 30°

Refractive index of glass block = 1.6

Angle of reflection = x

Angle of refraction = y

(a) By the law of reflection, angle of incidence i = angle of reflection r

$\therefore x = 30°$

(b) Using Snell's law,

$$n = \frac{\sin i}{\sin r}$$

$$1.6 = \frac{\sin 30°}{\sin y}$$

$$y = 18.2°$$

Daily phenomena and applications of refraction

'Bent' objects

Objects in water or other optically denser media appear bent because of refraction. In Figure 12.25, we can see the rod because it reflects light to our eyes. It appears to be bent because the reflected light from the immersed part of the rod refracts when it travels from water to air.

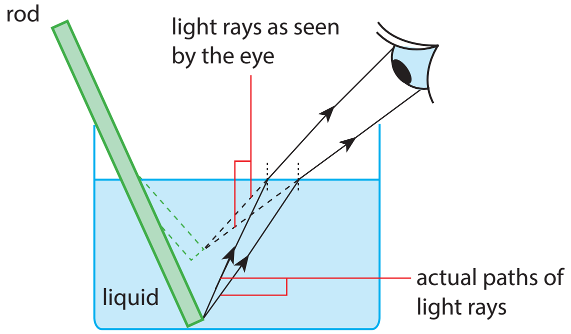


Figure 12.25 *A partially immersed rod appears bent because light bends away from the normal when it travels from water to air.*

Misperception of depth

Swimming pools appear shallower than they actually are because of refraction (Figure 12.26).

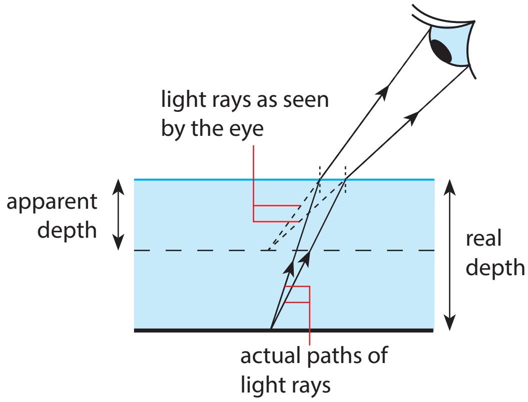


Figure 12.26 *A swimming pool is deeper than it seems.*

S

Worked Example 12G

Figure 12.27 shows a thin rod partially immersed in a beaker of water. Given that the refractive index of water is 1.33, determine the value of

(a) θ; **(b)** x.

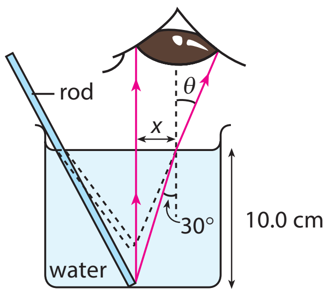


Figure 12.27

Solution

(a) We can solve for θ by reversing the direction of the light ray.

$$n = \frac{\sin\theta}{\sin 30°} \text{ (Snell's law)}$$

$$1.33 = \frac{\sin\theta}{\sin 30°}$$

$$\theta = 41.7°$$

(b) Since angle AOB and the angle of incidence are alternate angles, angle AOB is 30°.

$$\therefore \tan 30° = \frac{x}{10 \text{ cm}}$$

$$x = 5.77 \text{ cm}$$

HELPFUL NOTES

The refractive index n of a medium is also given by the ratio of the real depth of an object in a medium to its apparent depth in the same medium.

i.e. $n = \dfrac{\text{real depth}}{\text{apparent depth}}$

ENRICHMENT INFO

The Archer's Fish Secret

The archer fish uses a unique way to catch its prey. It shoots a jet of water with pinpoint accuracy, knocking its prey off a branch or a leaf. How is it able to hit its target with such high accuracy despite the visual distortion caused by refraction?

Biologists are still trying to establish an answer to this question. If you were an archer fish, how would you overcome distorted vision due to refraction so that you could always hit your target?

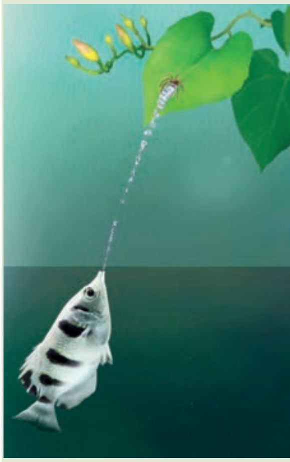


Figure 12.28 *An archer fish spitting a jet of water at its prey resting on a leaf*

Let's Practise 12.2

1 Draw a clearly labelled diagram to show the refraction of light when it travels from air to water.
2 S How is the speed of light in glass related to the angle of incidence and angle of refraction of light?
3 At what angle of incidence will light pass from air to another transparent material without being refracted?
4 Draw a diagram to show how a coin at the bottom of a bucket of water appears to a viewer.
5 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB
Exercise 12B, pp. XX–XX

12.3 Total Internal Reflection

In this section, you will learn the following:

- State the meaning of *critical angle*.
- Describe *internal reflection* and *total internal reflection* using both experimental and everyday examples.
- S Recall and use the equation $n = \dfrac{1}{\sin c}$.
- S Describe the use of optical fibres, particularly in telecommunications.

Figure 12.29 shows the reflection of a turtle under water. This reflection is at the water–air boundary and occurs due to the *total internal reflection* of light.

Total internal reflection can only occur when light passes from an optically denser to a less dense medium. To understand this unique behaviour of light, we need to first understand what *critical angle* is.

Figure 12.29 *The reflection of the turtle can be clearly seen underwater at the water–air boundary.*

What is a critical angle? How can we find it for a material?

We can carry out Let's Investigate 12D to demonstrate critical angle.

Let's Investigate 12D

Objective
To investigate the critical angle in total internal reflection

Apparatus
Transparent semi-circular block, ray box and power supply, paper

Precautions
A ray box with a filament lamp may get very hot.

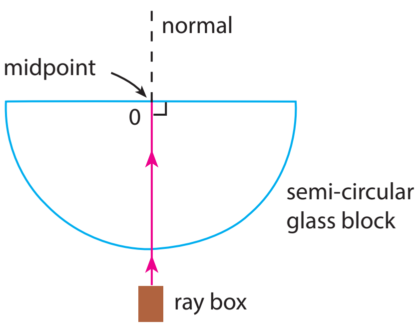


Figure 12.30

LINK PWB
Practical 12E, pp. XX–XX

Procedure

1 Set up the apparatus as shown in Figure 12.30.

2 Direct a light ray through the semi-circular block at the midpoint O such that it is perpendicular to the flat surface of the glass block. Observe the path of the light.

3 Direct the light ray at an angle *i* at O. Vary angle *i* and observe the corresponding change in the path of the light ray.

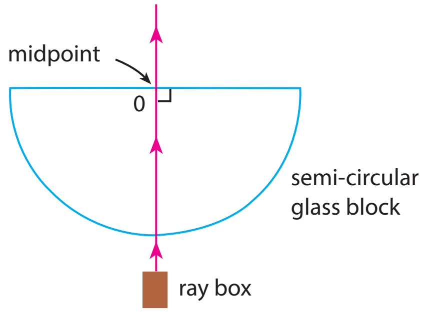


Figure 12.31

Observation, discussion and conclusion

1 When the light ray was directed through the midpoint O such that it was perpendicular to the flat surface of the block, the light ray passed straight through, without any deviation (Figure 12.31).

2 When the light ray was directed at a point O at an angle *i*, it refracted away from the normal upon emerging from the glass (Figure 12.32). This is because it was travelling from an optically denser medium (e.g. glass) to an optically less dense medium (e.g. air). A small amount of light is reflected off the flat surface of the glass block.

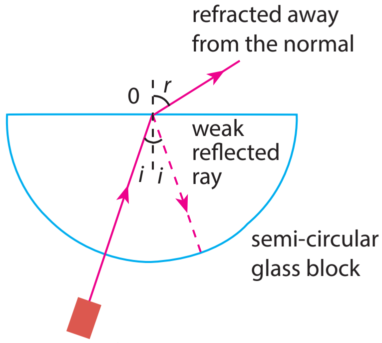


Figure 12.32

3 As the incident angle is increased, the refracted ray bends further away from the normal until the angle of refraction *r* becomes 90° (Figure 12.33). When the angle of refraction is 90°, the corresponding angle of incidence is known as the *critical angle c*.

The **critical angle** *c* is defined as the angle of incidence (in an optically denser medium) for which the angle of refraction (in the optically less dense medium) is 90°.

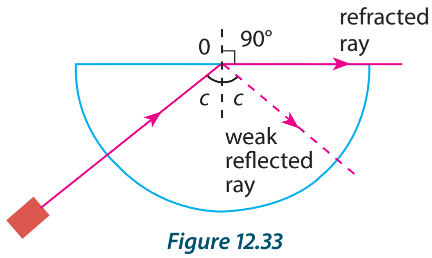


Figure 12.33

HELPFUL NOTES

In Investigation 12D, a semi-circular glass block is used, and the light ray is always directed towards the midpoint O of the diameter of the block.

Recall that a tangent to a circle is perpendicular to the radius at the point of contact (Figure 12.34).

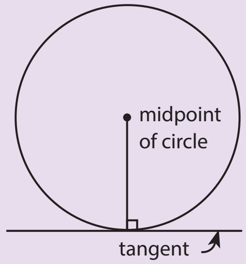


Figure 12.34

Therefore, a light ray directed towards the midpoint O will always enter the curved surface of the glass block at an angle of incidence of 0° (i.e. it passes through the surface without bending). This makes the study of critical angle at the flat surface of the glass block more convenient.

Critical angle and total internal reflection

When the angle of incidence in the glass block is larger than the critical angle *c*, the light ray reflects off the flat surface of the glass block. There is no refraction at the flat surface (i.e. glass–air boundary) (Figure 12.35). This phenomenon is known as *total internal reflection*. This explains why we can see the reflection of the turtle underwater in Figure 12.29 on page 192.

Total internal reflection is the complete reflection of a light ray inside an optically denser medium at its boundary with an optically less dense medium.

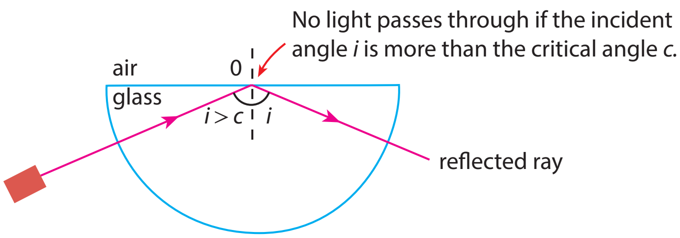


Figure 12.35

ENRICHMENT
THINK

Radio waves transmitted from the ground can undergo total internal reflection from the sky. The waves are reflected off the ionosphere, an upper layer of the Earth's atmosphere, and can be received many hundreds of kilometres away. Explain how the ionosphere causes the total internal reflection of the waves.

PHYSICS WATCH

Scan this page to watch a clip of an experiment on total internal reflection.

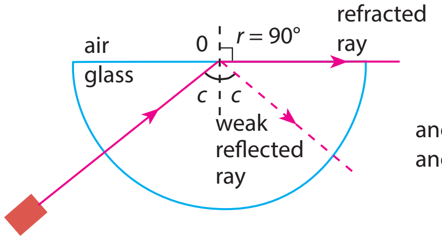
In summary, two conditions that must be satisfied in order for a light ray to undergo total internal reflection are:

1 The light ray in an optically denser medium strikes its boundary with an optically less dense medium.

2 The angle of incidence is greater than the critical angle of the optically denser medium.

S Determining critical angle

Given the refractive index n of a transparent material, we can find its critical angle c. Consider a light ray travelling from air into a semi-circular glass block before exiting into air at O (Figure 12.36).



angle of incidence i = critical angle c
angle of refraction $r = 90°$

Figure 12.36

With reference to page 188, when the light is travelling from vacuum to the medium, the refractive index of the medium is given by the ratio $\frac{\sin\text{ (angle of incidence)}}{\sin\text{ (angle of refraction)}}$. However, in Figure 12.36, the light is travelling from glass to air. We can visualise the same path of light in Figure 12.36 but with the directions reversed (refer to Figure 12.23 on page 190). This will give the following:

$$n = \frac{\sin 90°}{\sin c} = \frac{1}{\sin c}$$

$$\therefore \mathbf{\sin c = \frac{1}{n}}$$

Worked Example 12H

Figure 12.37 shows a light ray entering a right-angled glass prism of refractive index 1.5.

(a) Calculate the critical angle of the prism.

(b) Complete the path of the light ray until it emerges into the air.

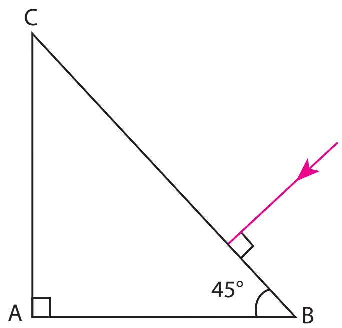


Figure 12.37

Solution

(a) Given: Refractive index $n = 1.5$

$$\sin c = \frac{1}{n} = \frac{1}{1.5}$$

$$c = 41.8°$$

(b) Since the ray enters the prism at a right angle, it does not bend and hits surface AB at 45° (i.e. angle of incidence i).

Since the angle of incidence (45°) is greater than the critical angle of 41.8°, total internal reflection occurs. Similarly, total internal reflection also occurs at surface AC. The light ray exits at a right angle to surface BC.

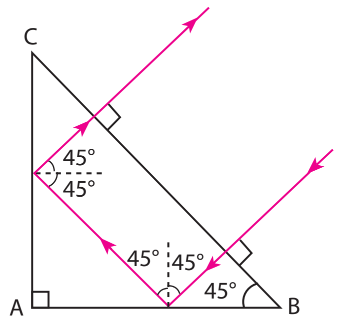


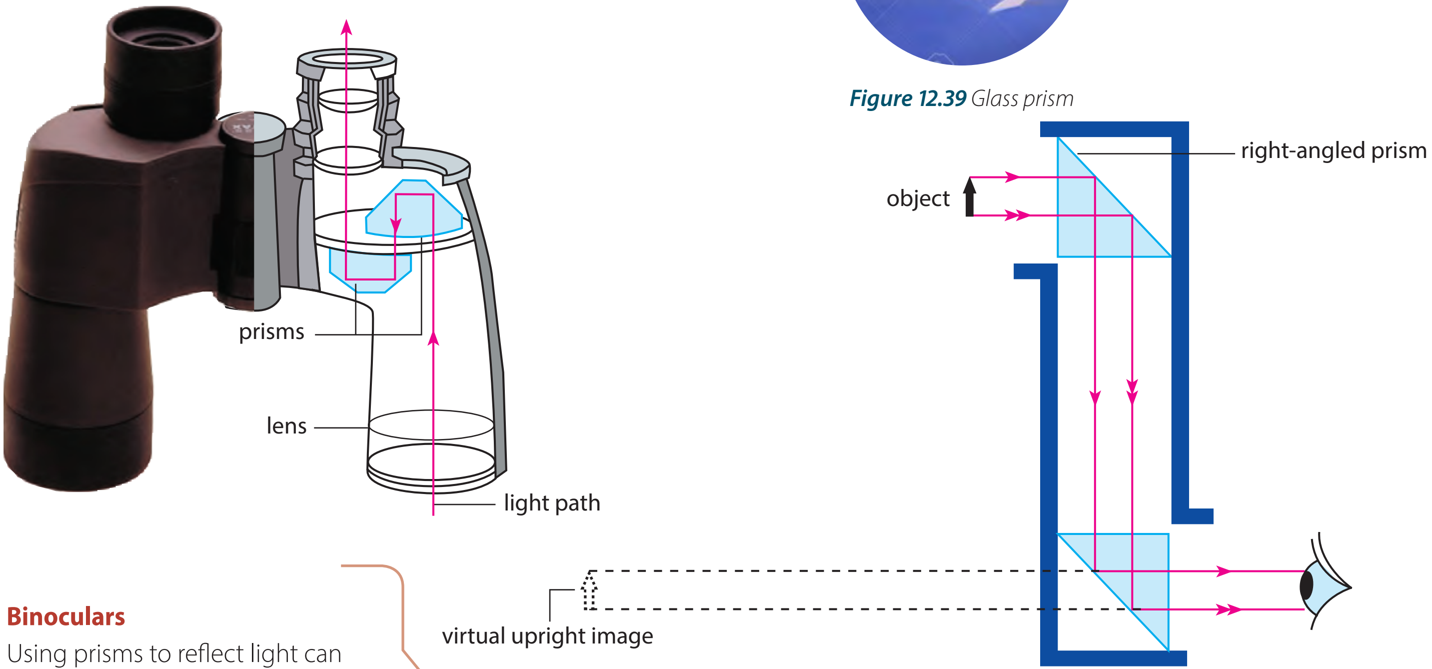
Figure 12.38

What are the applications of total internal reflection?

Glass prisms

Glass prisms (Figure 12.39) are used to reflect light in some optical instruments such as binoculars and periscopes. They reflect light by total internal reflection.

Figure 12.39 Glass prism



Binoculars
Using prisms to reflect light can reduce the size of binoculars. Prisms also rectify the inverted image, produced by the lenses in binoculars, to an upright image.

Periscopes
Prisms can be used in place of plane mirrors to give clearer images. They reflect light to allow us to see an upright image.

Total Internal Reflection in Glass Prisms

Single Lens Reflex (SLR) cameras
Prisms in SLR cameras allow photographers to see the exact image to be captured. A five-sided prism (pentaprism) helps to make this feature possible in an SLR camera.

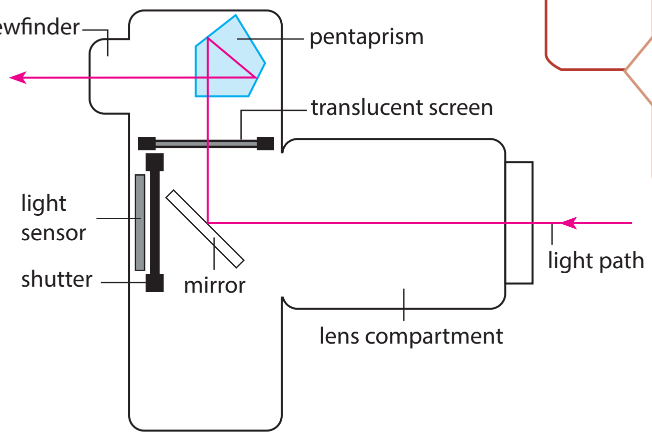


Figure 12.40 Use of total internal reflection in glass prisms

QUICK CHECK

The diagram of the binoculars in Figure 12.40 shows total internal reflection occurring twice.

True or false?

Optical fibres

The transmission of data using optical fibres is an important application of total internal reflection. Optical fibres are long, thin and flexible. They are made of glass or plastic and can transmit light over long distances through total internal reflection (Figure 12.41).

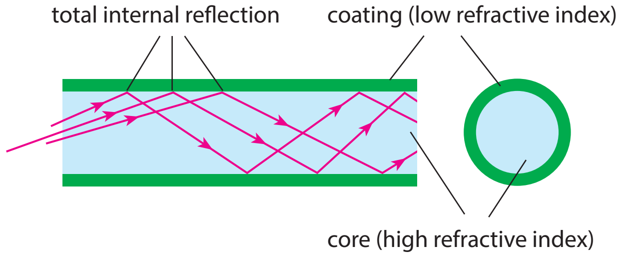


Figure 12.41 *An optical fibre has a core of a high refractive index. The core is coated with another material of a lower refractive index.*

Even when the fibre is bent, light rays entering it will still be internally reflected at the boundary between the two refractive materials. These flexible fibres have innovative uses in many industries such as telecommunications and medicine (Figure 12.42).

Total Internal Reflection in Optical Fibres

Telecommunications industry

Today, telephone conversations and Internet data are transmitted across continents using optical fibres, and not copper wires. Advantages of optical fibres over copper wires in telecommunications are as follows:

- *Higher carrying capacity:* An optical fibre can carry much more information over long distances than a copper wire.
- *Less signal degradation:* A signal transmitted via optical fibres experiences much less signal loss as compared to copper wires.
- *Lightweight:* Optical fibres are lighter than copper wires.
- *Lower cost:* Optical fibres are becoming cheaper to manufacture as compared to copper wires of equivalent lengths.

Medical industry

The high flexibility of optical fibres makes them ideal for medical applications such as endoscopes. Doctors use endoscopes to see inside hollow organs, such as the intestines.

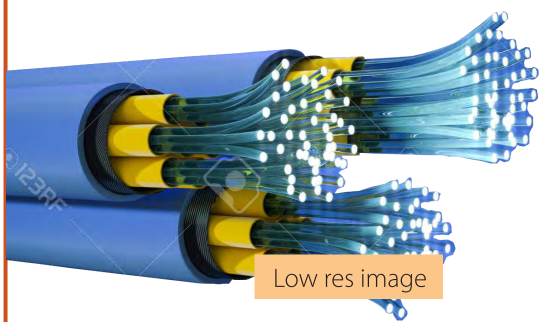


Figure 12.42 *Use of total internal reflection in optical fibres*

Let's Practise 12.3

1. Explain what is meant by term *critical angle*.
2. Draw a clearly labelled diagram to show total internal reflection.
3. S The refractive index of a glass prism is 1.9. Calculate its critical angle.
4. State **two** applications of total internal reflection.
5. **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK

Exercise 12C, pp. XX–XX

12.4 Refraction by Thin Lenses

In this section, you will learn the following:

- Describe the action of thin converging and thin diverging lenses on a parallel beam of light.
- Define and use the terms *focal length*, *principal axis* and *principal focus (focal point)*.

A lens is a piece of clear plastic or glass with curved surfaces. Lenses are widely used in cameras, spectacles, projectors and many other optical instruments.

Figure 12.43 *Camera with interchangeable lenses*

Figure 12.44 *How are spectacles for long-sightedness different from those for short-sightedness?*

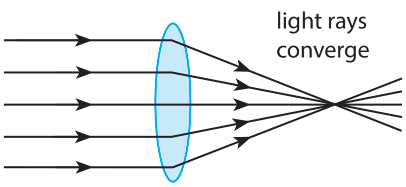
WORD ALERT

Converge: heading towards a point

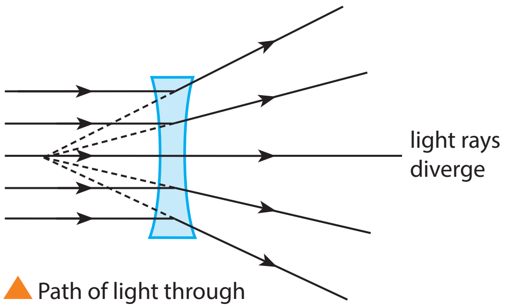
Diverge: spread out

What determines the path of light through a lens?

A typical lens can be thought of as a set of small prisms (Figures 12.45). As the surface of a lens is curved, parallel light rays hitting different parts of its surface have different incident angles. This causes the individual rays to refract by different angles. The angle of refraction is the largest at the outermost part of the lens, while no refraction occurs in the middle. As a result, depending on the curvature of the lens, light rays either converge or diverge after passing through the lens (Figure 12.44).



Path of light through a converging lens



Path of light through a diverging lens

Figure 12.45 *A typical lens can be thought of as a set of small prisms.*

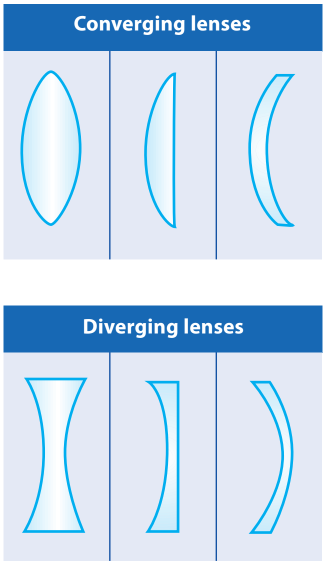


Figure 12.46 *Different types of converging and diverging lenses*

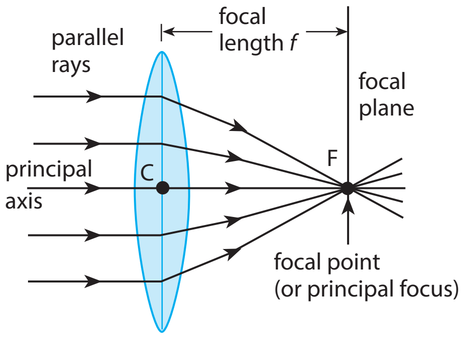
A **converging lens** causes light rays to converge to a point. It is *thicker in the centre*.

A **diverging lens** causes light rays to diverge from a point. It is *thinner in the centre*.

Thin converging lens

We will learn what focal length is and other terms that are used to describe a thin converging lens (Figure 12.47).

The **principal axis** is the horizontal line passing through the optical centre of the lens. It is perpendicular to the vertical plane of the lens.



Focal length *f* is the distance between the optical centre C and the focal point F.

The *optical centre* C is the midpoint between the surfaces of the lens on its principal axis. Rays passing through the optical centre are not refracted.

The **principal focus (or focal point)** is the point at which all rays parallel to the principal axis converge after refraction by the lens. A lens has two focal points, one on each side of the lens.

The *focal plane* is the plane that passes through the focal point F and perpendicular to the principal axis.

Figure 12.47 *Parallel beam of rays parallel to the principal axis*

When the parallel beam of rays incident on a thin converging lens is not parallel to the principal axis, the rays are refracted to a point (not the focal point F) on the focal plane (Figure 12.48).

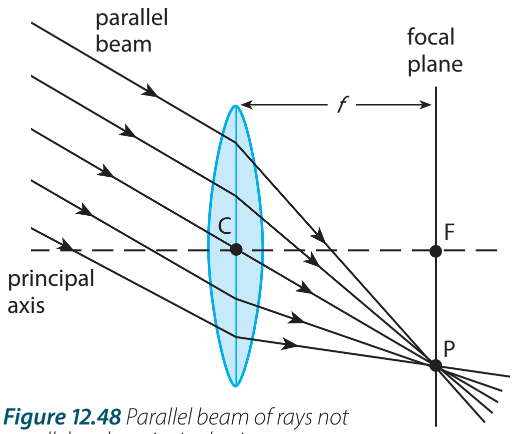


Figure 12.48 *Parallel beam of rays not parallel to the principal axis*

Let's Practise 12.4

1. With the help of a diagram, describe how a converging lens is different from a diverging lens in terms of their structure and their effect on light.
2. Figure 12.50 shows a diagram of light rays passing through a thin converging lens. Explain whether the diagram is correct?
3. With the help of a diagram, define the focal length of a thin converging lens.
4. **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

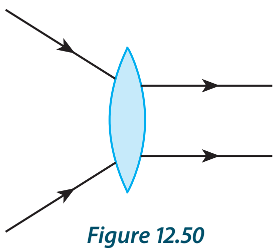


Figure 12.50

ENRICHMENT *ACTIVITY*

In this activity, you will use the rays of the Sun to find the focal length of a magnifying glass.

Precaution

Be careful! The bright spot may cause the paper (or anything else) to burn.

1. Hold a magnifying glass above a piece of paper under the Sun.
2. Adjust the distance between the lens and the paper until you can observe a small bright spot. This distance is its focal length.

At its focal length, a magnifying glass focuses the Sun's rays onto one small spot on its focal plane (Figure 12.49).

Figure 12.49

Can you think of other ways to find the focal length of a magnifying glass?

LINK TWB

Exercise 12D, pp. XX–XX

12.5 Ray Diagrams for Thin Converging Lenses

In this section, you will learn the following:
- Describe the characteristics of an image.
- Know how a virtual image is formed.
- Draw and use ray diagrams to show how a real image is formed.
- S Draw and use ray diagrams to show how a virtual image is formed.
- S Describe the use of a single lens as a magnifying glass.
- S Describe the use of converging and diverging lenses to correct long-sightedness and short-sightedness.

From Section 12.4, we know that
- any light ray passing through the optical centre C of a lens is not refracted;
- any light ray parallel to the principal axis of a lens will converge at the focal point F (Figure 12.51).

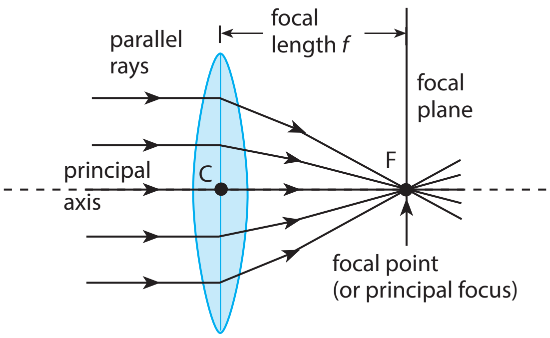
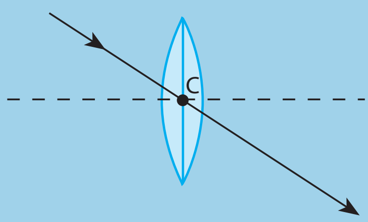
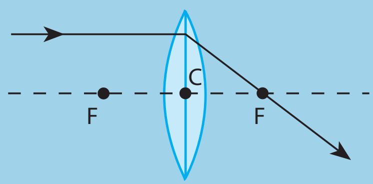
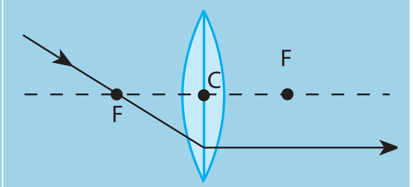


Figure 12.51

With this, we can identify three particular light rays that behave in a predictable way whenever they pass through any thin converging lens (Table 12.3).

Table 12.3 *Behaviour of three particular light rays when passing through a thin converging lens*

Ray 1 passes through optical centre C	Ray 2 parallel to principal axis	Ray 3 passing through focal point F
		
An incident ray through the optical centre C passes without bending.	An incident ray parallel to the principal axis is refracted to pass through F.	An incident ray passing through the focal point F is refracted parallel to the principal axis.

Where is the image made by a thin converging lens?

The image of a lens is determined by the relative positions of the focal point and the object distance. Using any two of the three rays mentioned in Table 12.3, we can draw a ray diagram to locate the position of an image produced by a thin converging lens.

Object distance longer than the focal length (i.e. $f < u < 2f$)

Figure 12.52 shows how a real image is formed when the distance of the object is longer than the focal length.

Step 1: Set up the ray diagram

- **i** Draw a horizontal line to represent the principal axis.
- **ii** Draw a double-headed arrow perpendicular to the horizontal line to represent the converging lens.
- **iii** The intersection point of the principal axis in **(i)** and the lens in **(ii)** is the optical centre of the converging lens. Label the point C.
- **iv** Label the focal point F of the lens on the principal axis. The distance CF is the focal length *f* of the lens.

Step 2: Place the object on the left of the lens

- **i** Draw a vertical arrow on the left of the lens to represent an object. Label the object O.
- **ii** Label the distance OC *u*. Note that $f < u < 2f$.

Step 3: Trace the rays and locate the image

- **i** Select and draw any two of the three rays, e.g. ray 1 and ray 2, from the tip of the object.
- **ii** The intersection point of the two rays represents the real image of the tip of the object. Complete the real image by drawing an arrow and labelling it I.

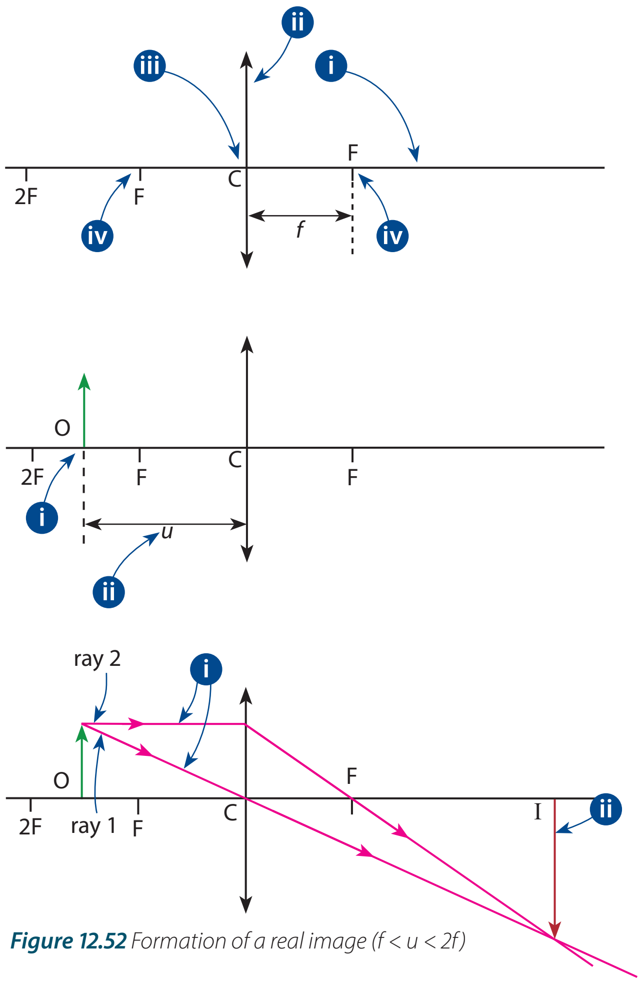


Figure 12.52 *Formation of a real image ($f < u < 2f$)*

Object distance shorter than the focal length (i.e. $u < f$)

Place the same object at a distance less than the focal length and draw the ray diagram (Figure 12.53). We can see that the light rays diverge and the intersection point of ray 1 and ray 2 can be found only if the rays are extended backwards.

When the diverging rays enter our eyes, they appear to come from a point on the same side as the object. The point represents the virtual image of the tip of the object and the broken arrow represents the virtual image of the object.

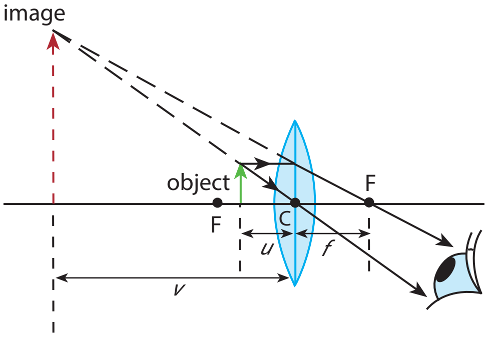
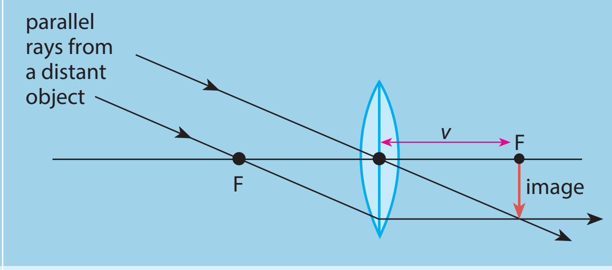
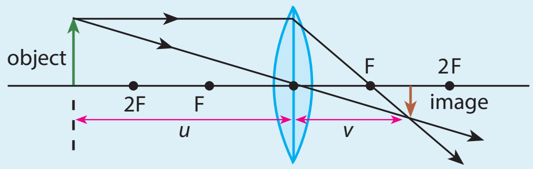
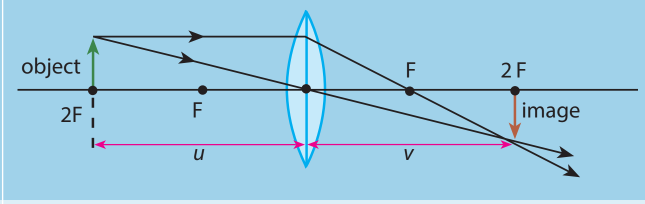
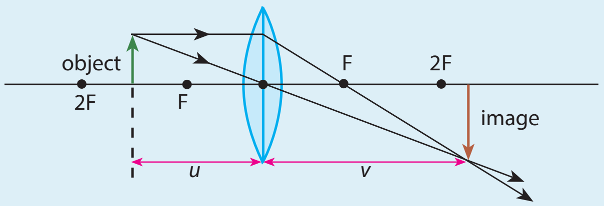
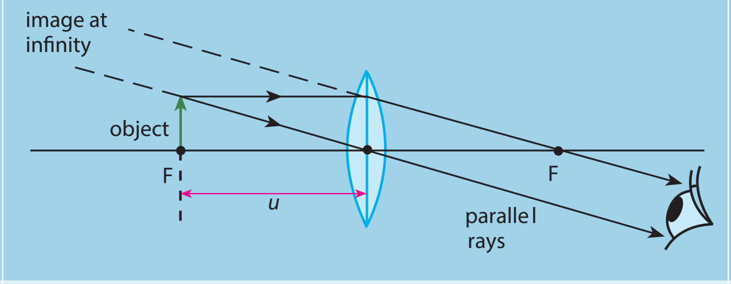
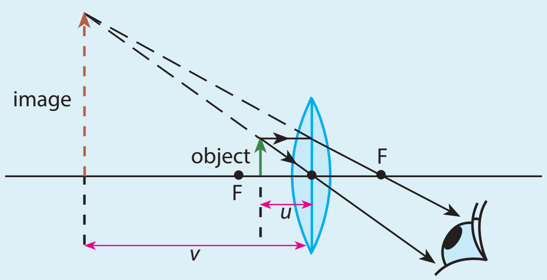


Figure 12.53 *Formation of a virtual image ($u <2f$)*

The distance of an object from a thin converging lens determines the type of image that is formed. Table 12.4 shows the types of images formed when an object is placed at different distances from the lens.

Table 12.4 *Types of images formed by a thin converging lens with different range of values of u*

Object distance (u)	Ray diagram	Type of image	Image distance (v)	Uses
$u = \infty$		• inverted • real • diminished	$v = f$ • opposite side of the lens	• object lens of a telescope
$u > 2f$		• inverted • real • diminished	$f < v < 2f$ • opposite side of the lens	• camera • eye
$u = 2f$		• inverted • real • same size	$v = 2f$ • opposite side of the lens	• photocopier making same-sized copy
$f < u < 2f$		• inverted • real • magnified	$v > 2f$ • opposite side of the lens	• projector • photograph enlarger
$u = f$		• upright • virtual • magnified	• image at infinity • same side of the lens	• eyepiece lens of a telescope
$u < f$		• upright • virtual • magnified	• image is behind the object • same side of the lens	• magnifying glass

PHYSICS WATCH

Scan this page to explore a simulation on formation of images by lenses.

From Table 12.4, we can see that

- when $u > f$, the image formed is real, inverted and on the opposite side of the lens as the object;
- when $u \leq f$, the image formed is virtual, upright and on the same side of the lens as the object.

Worked Example 12I

An object 2 cm high is placed 7.5 cm from a thin converging lens. The focal length of the lens is 5 cm.

(a) Find, by scale drawing, the position of the image formed.

(b) State the characteristics of the image.

Solution

(a) Horizontal scale: 1 unit square represents 1 cm

Vertical scale: 1 unit square represents 1 cm

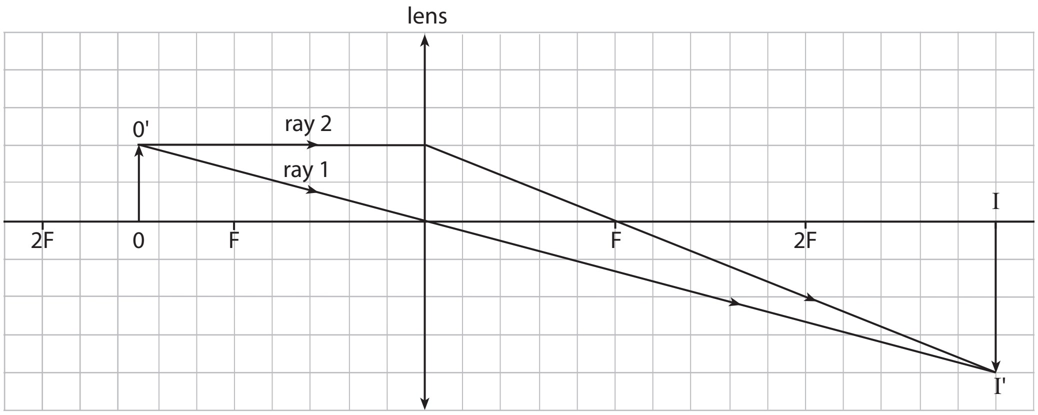


Figure 12.54

From Figure 12.54, the image distance is 15 cm from the lens.

(b) The image formed is real, inverted and magnified. It is on the opposite side of the lens.

LINK PWB

Practical 12F, pp. XX–XX

What can lenses be used for?

Magnifying glass

A magnifying glass is a thin converging lens. It is used to make objects look bigger (Figure 12.55). In order to get a magnified image, the lens should be positioned at a distance less than a focal length f from the object (i.e. $u < f$).

Figure 12.55 *In comparison to the rest of the textbook cover, the letters under the magnifying glass are magnified.*

Visual correction for long-sightedness

People who are long-sighted are unable to see objects close to their eyes clearly. The lenses in their eyes are unable to focus a clear image of a close object on the retina (Figure 12.56).

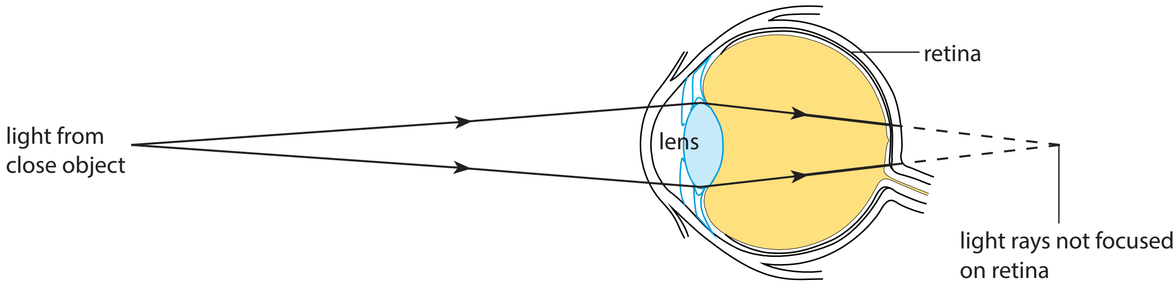


Figure 12.56 *Long-sightedness — the eye lens is unable to focus the light rays onto the retina*

Spectacles with converging lenses can be used to partially converge the light rays before they enter the eyes (Figure 12.57). This way, the light rays coming from the object can be focused on the retina to produce a sharp image.

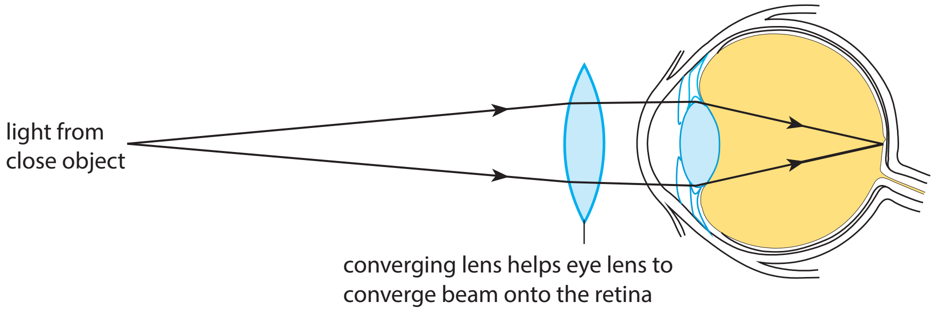


Figure 12.57 *Correcting long-sightedness using a converging lens*

Visual correction for short-sightedness

A person is short-sighted when his or her eyeball is longer than normal along the horizontal axis from the lens to the retina. The eye can still focus on near objects. However, parallel light rays from distant objects are focused in front of the retina, forming a blurred image (Figure 12.58).

Short-sightedness can be corrected by wearing spectacles with concave lenses. The concave lenses diverge the rays from distant objects before they reach the eye. The diverged rays can then be focused onto the retina and this will enable the person to see distant objects clearly (Figure 12.59).

PHYSICS WATCH

Scan this page to explore a simulation on short-sightedness and long-sightedness.

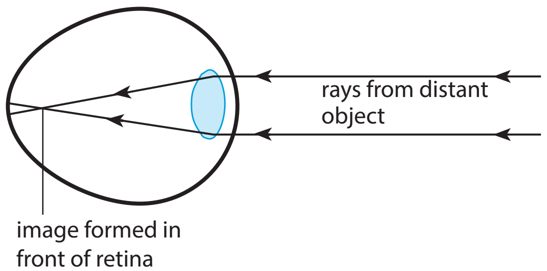


Figure 12.58 *Short-sightedness — image forms in front of the retina*

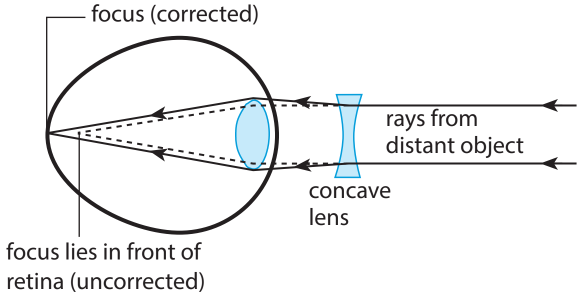


Figure 12.59 *Correcting short-sightedness with a concave lens*

Worked Example 12J

Figure 12.60 shows a small object of height 1.0 cm placed 1.4 cm away from a thin converging lens L of focal length 1.9 cm.

By drawing a suitable ray diagram,

(a) find the position and height of the image;

(b) describe the characteristics of the image formed.

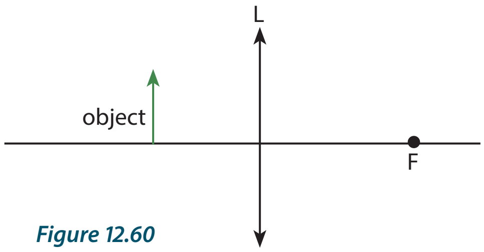


Figure 12.60

Solution

Given: Size of object OO′ = 1.0 cm, object distance $u = 1.4$ cm, focal length $f = 1.9$ cm

(a) By scale drawing, the image distance v is 5.8 cm and the height of image I′ is 3.9 cm.

(b) The image formed is upright, magnified, virtual and on the same side of the lens as the object.

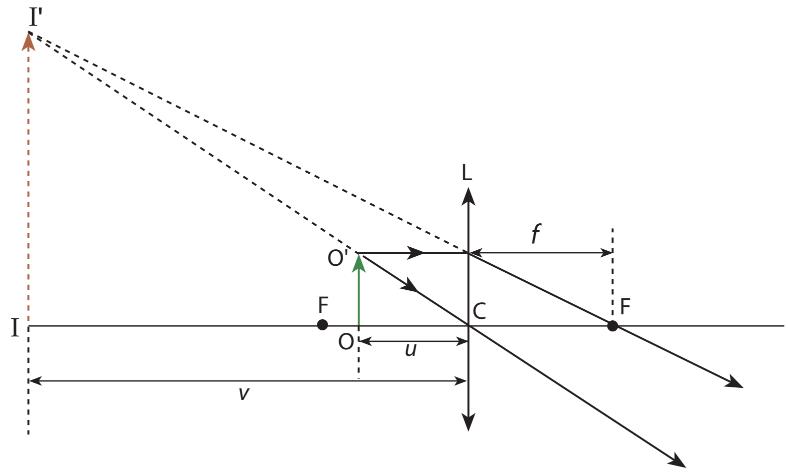


Figure 12.61

Let's Practise 12.5

1 Describe how far an object should be placed from a thin converging lens to produce

(a) a magnified real image;

(b) S a magnified virtual image.

2 S State **two** applications of converging lenses.

3 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

Exercise 12E, pp. XX–XX

12.6 Dispersion of Light

In this section, you will learn the following:

- Describe the dispersion of light as illustrated by the refraction of white light by a glass prism.
- Know the traditional seven colours of the visible spectrum in order of frequency and in order of wavelength.
- S Recall that visible light of a single frequency is described as monochromatic.

We have seen in this chapter that light can be refracted when it travels from one medium to another. So far, we have assumed that all wavelengths of light travel at the same speed. This is true in the vacuum of space, yet it is merely an approximation in all other media.

Isaac Newton performed a famous experiment where he placed a glass prism in the path of a thin beam of white light from the Sun (Figure 12.62).

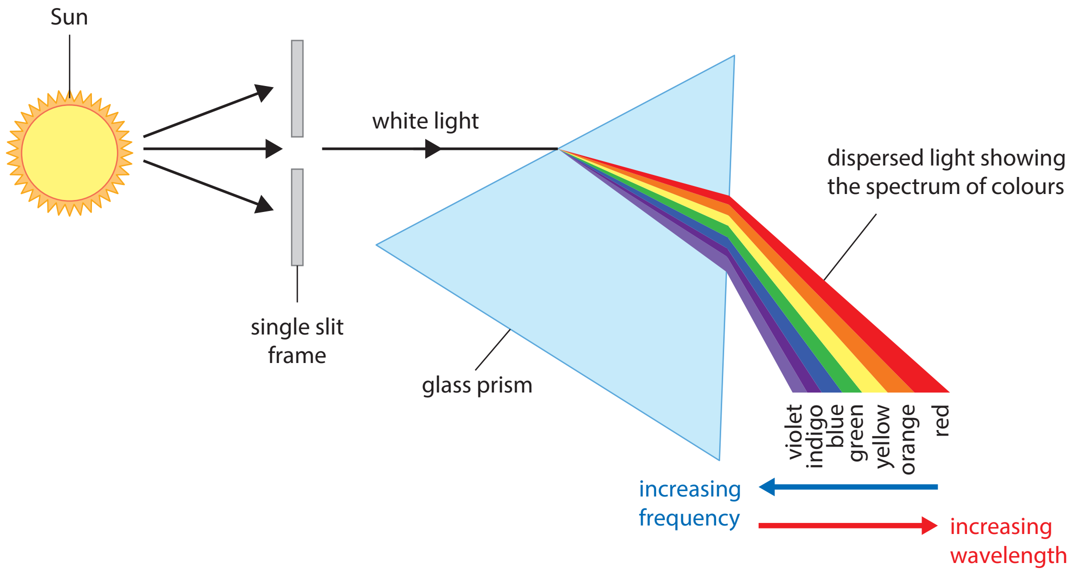


Figure 12.62 *Newton's dispersion experiment to show the spectrum of visible light*

The different colours that Newton observed is called a **spectrum**. The spectrum is shown in Figure 12.62 from red to violet in order of increasing frequency and decreasing wavelength. Red light has the lowest frequency and violet light has the highest.

It arises because the refractive index for each of the colours in the spectrum have a slightly different refractive index. The refractive index for red light is the lowest of all the visible colours, whereas violet light has the highest of the visible colours. This change in refractive index across the spectrum is known as **dispersion**.

S Although there are traditionally seven colours in the visible spectrum, there are an infinite number of different frequencies between red light and violet light. Any single frequency of light is described as **monochromatic**.

Let's Practise 12.6

1. State the order of colours of the visible spectrum, starting with the shortest wavelength.
2. Explain which of the colours of the visible spectrum travels fastest in glass.
3. **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

HELPFUL NOTES

To help you remember the seven colours of the visible spectrum, remember this acronym: **ROYGBIV**

QUICK CHECK

Red light has the longest wavelength in the visible spectrum.

True or false?

LINK

The spectrum of visible light is part of the electromagnetic spectrum. Find out more in Chapter 13.

LINK

TWB

Exercise, 12 F–12G, pp. XX–XX

Exercise 12H Let's Reflect, p. X

Let's Map It

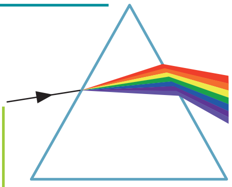
LIGHT

LIGHT undergoes **Reflection**

LIGHT undergoes **Refraction**

Refraction causes **Dispersion**

Dispersion produces



Seven colours of the visible spectrum

Reflection and Refraction: of which image position can be located by **Ray diagrams**

Ray diagrams described by terms such as
- Incident ray
- Reflected/refracted ray
- Point of incidence
- Normal
- Angle of incidence
- Angle of reflection/refraction

Reflection is governed by

Law of reflection
Angle of incidence i = angle of reflection r

Reflection by a plane mirror

Image formed
- is the same size as the object
- is laterally inverted
- is upright
- is virtual
- has the same distance from the mirror as the object

Refraction is governed by

S **Law of refraction** (Snell's law)
$\frac{\sin i}{\sin r}$ = constant

Law of refraction defines

S **Refractive index**

$$n = \frac{\text{sin (angle of incidence in vacuum)}}{\text{sin (angle of refraction in medium)}}$$
$$= \frac{\text{(speed of light in vacuum)}}{\text{(speed of light in medium)}}$$

Law of refraction explains

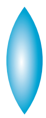
Total internal reflection

occurs when
- Light travels from an optically denser medium to an optically less dense medium.
- Angle of incidence in the optically denser medium is greater than the critical angle c.

S $\sin c = \frac{1}{n}$

Applications
- glass prism
- S optical fibre

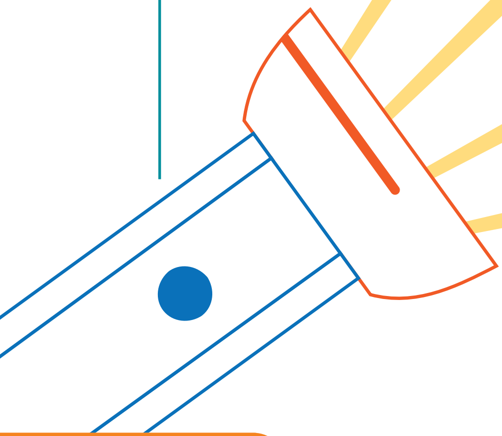
Law of refraction apply to refraction in



Thin converging lens

described by terms such as
- focal length
- principal axis
- optical centre
- focal point
- focal plane

S Applications
- magnifying glass
- spectacle lenses



Let's Review

Section A: Multiple-choice Questions

1 Which characteristics best describe an image formed in a plane mirror?

A Diminished and virtual
B Same size and virtual
C Same size and real
D Magnified and virtual

2 Which statement about the size of an image formed in a plane mirror image is false?

A The image can be taller than the mirror.
B The image height depends on the object distance.
C The image height depends on the object height.
D The width of the image is the same as that of the object.

3 (S) A girl stands at point P as shown in Figure 12.63. A wall separates her from four other persons standing at points W, X, Y and Z. It blocks her direct line of sight to them. If a mirror is placed as shown in the diagram, how many persons can she see reflected in the mirror?

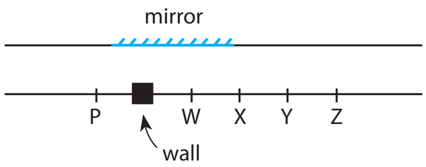


Figure 12.63

A 1 **B** 2
C 3 **D** 4

4 (S) Figure 12.64 shows the complete path of a light ray travelling from air to a liquid.

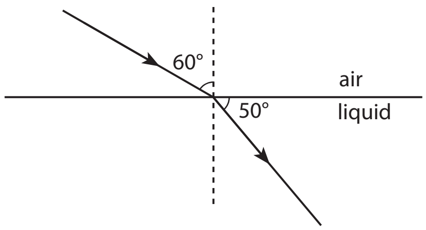


Figure 12.64

The refractive index of the liquid is given by

A $\frac{\sin 60°}{\sin 50°}$ **B** $\frac{\sin 30°}{\sin 50°}$

C $\frac{\sin 60°}{\sin 40°}$ **D** $\frac{\sin 40°}{\sin 50°}$

5 A light ray in air is incident at an angle on one side of a rectangular glass block (Figure 12.65).

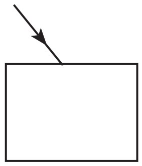
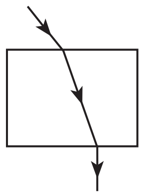
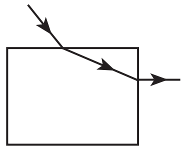
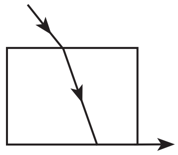


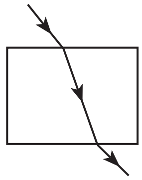
Figure 12.65

Which ray diagram correctly describes the complete path of the light ray?

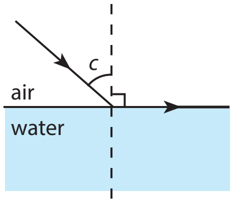
A


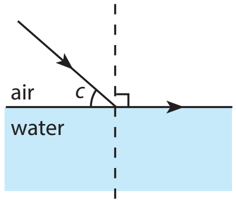
B


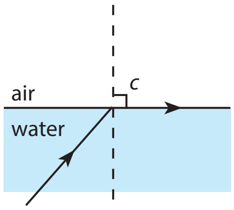
C


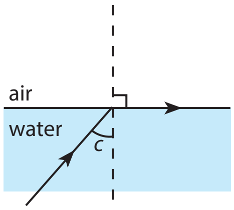
D


6 Which diagram correctly describes the critical angle *c* for an air–water surface?

A


B


C


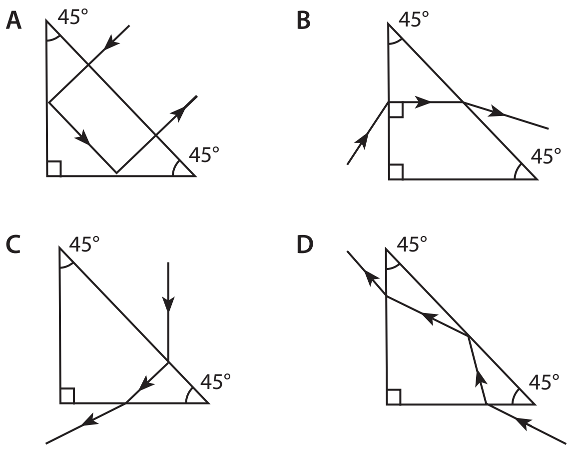
D


7 The fish in a pond appears to be

A deeper in the water than it really is because light reflected from the fish will refract towards the normal.
B deeper in the water than it really is because light reflected from the fish will refract away from the normal.
C nearer to the surface than it really is because light reflected from the fish will refract towards the normal.
D nearer to the surface than it really is because light reflected from the fish will refract away from the normal.

Let's Review

8 The critical angle for an air–glass interface is 42°. Which diagram shows the incorrect path of a light ray passing through a glass prism?



9 A thin converging lens is used to focus the rays from the Sun onto a piece of paper. When the rays burn a hole in the paper, the distance between the lens and the paper is ____________ the focal length of the lens.

A less than half B equal to half

C equal to D equal to twice

10 Figure 12.66 shows the position of an object relative to a lens. At which position should a viewer's eyes be to see a magnified and clear image of the object?

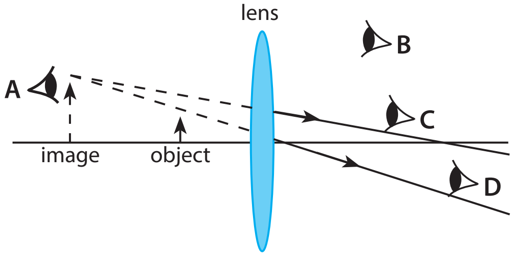


Figure 12.66

11 A person attempts to measure the focal length of a lens, as shown in Figure 12.67.

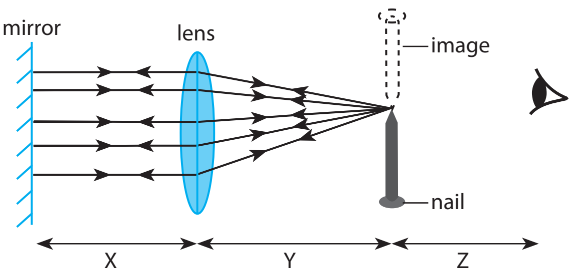


Figure 12.67

Which distance is the focal length of the lens?

A X B Y

C Z D X + Y

12 An object is placed in front of a converging lens of focal length *f*, as shown in Figure 12.68.

At which position will the image be formed?

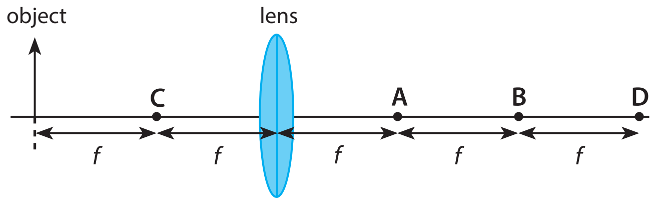


Figure 12.68

13 **S** The image formed by a slide projector on the screen is

A real, inverted and diminished.

B real, inverted and magnified.

C virtual, upright and diminished.

D virtual, upright and magnified.

14 Which of the following is the correct term for the splitting up of light when it passes through a medium?

A Diffraction B Dispersion

C Interference D Reflection

15 **S** Which of the following is the correct term for light of a single colour?

A Achromatic B Dichromatic

C Monochromatic D Polychromatic

Section B: Short-answer and Structured Questions

1 (a) Figure 12.69 shows a large letter F placed in front of a plane mirror with two incident rays.

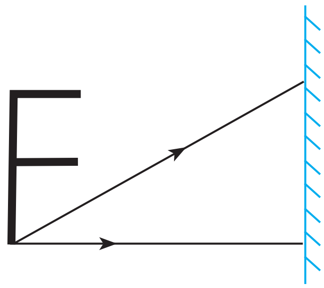


Figure 12.69

(i) Using the law of reflection, locate the position and draw the image of F.

(ii) State the characteristics of the image of F.

(b) Figure 12.70 shows a person looking at the image of a test card in a plane mirror. Find the distance from his eyes to the image of the card.

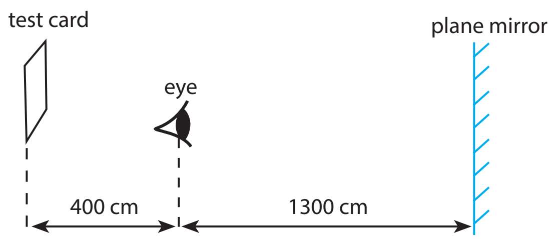


Figure 12.70

2 **(a)** What is refraction?

(b) S Figure 12.71 shows the path of a light ray from air through a glass block and into air again.

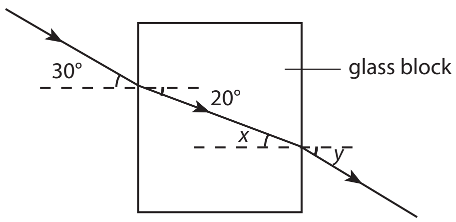


Figure 12.71

(i) Determine the refractive index of the glass.

(ii) State the angles *x* and *y*.

3 S The refractive indices of some transparent materials are shown in Table 12.5.

Table 12.5

Medium	Refractive index *n*
Diamond	2.4
Perspex	1.5
Water	1.33
Air	1.000 293

(a) For the same angle of incidence,

(i) which medium will cause light to bend the most?

(ii) which medium will cause light to bend the least? Explain your choice in each case.

(b) Given that the refractive index of flint glass is 1.7 and the speed of light in air is 300 000 km/s, what is the speed of light in flint glass?

(c) Given that the speed of light in crown glass is 200 000 km/s and the speed of light in air is 300 000 km/s, what is the refractive index of crown glass?

4 S

(a) Given that the refractive index of water is 1.33, find the angle of refraction of a light ray at the water–air boundary in Figure 12.72.

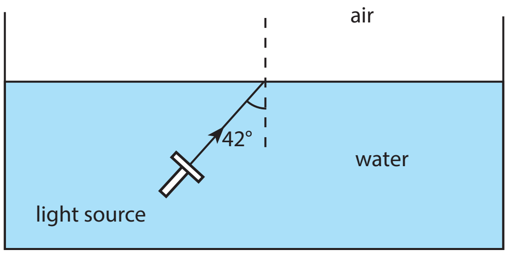


Figure 12.72

(b) Calculate the critical angle of water. Then draw, in Figure 12.72, the refracted ray and the reflected ray when the critical angle is reached.

5 S

(a) Figure 12.73 shows a light ray incident on a right-angled prism of refractive index 1.5. Using Snell's law, calculate the angle of refraction of the ray within the prism.

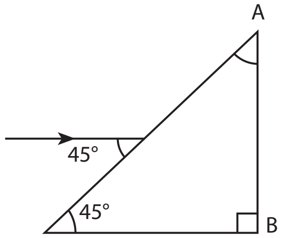


Figure 12.73

(b) Determine whether this ray within the prism will undergo total internal reflection when it hits the face AB of the prism.

6 A converging lens is used to project a 250-mm image of a square slide onto a screen 1000 mm away. The focal length of the lens is 200 mm. By means of a scale drawing, determine

(a) the distance of the slide from the lens;

(b) the size of the slide.

Let's Review

7 S Figure 12.74 shows a lady of height 1.5 m looking into a vertical plane mirror GH. Her eyes are 10 cm below the top of her head.

Figure 12.74

(a) By drawing a ray diagram, determine

(i) the minimum length of the mirror that allows the lady to see a full-length image of herself;

(ii) the height of the bottom of this mirror above the floor.

(b) Suppose that the mirror is moved away from the person at a speed of 1 m/s. Determine the speed at which the image appears to move and state the direction of its movement.

8 **(a)** A sheet of white paper and a polished metal surface each reflects a parallel beam of light. With the help of diagrams, explain how the reflections by the paper and the metal differ.

(b) S A bus driver has placed the centre of a 20-cm-wide plane mirror 50 cm in front of him. The rear of the bus is 500 cm directly behind the plane mirror. How wide is the driver's rear field of vision whenever he looks into the mirror while driving?

9 Figure 12.75 shows the behaviour of a light ray passing through an optical fibre from one end A to the other end B.

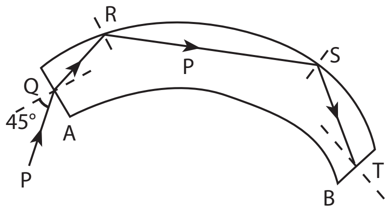


Figure 12.75

(a) **(i)** Explain why the light ray changes direction at Q.

(ii) Explain why the light ray undergoes total internal reflection at R and S.

(b) S If the refractive index of the glass that is used to make the optical fibre is 1.5, calculate the angle of refraction at Q.

(c) On Figure 12.75, draw the path of the light ray after refraction at T.

(d) S State **two** advantages of using optical fibres instead of copper wires in telecommunications.

10 Explain, with the aid of a diagram, how a rainbow is formed in the sky.

CHAPTER 13

Electromagnetic Spectrum

PHYSICS WATCH

Scan this page to watch a clip about electromagnetic waves around us.

QUESTIONS

- Name a few examples of wireless electronic gadgets.
- Where does the information come from?
- How does information travel through air?

We live in a technologically advanced world, where more and more electronic gadgets are going wireless. It seems like these gadgets are able to detect and receive information out of thin air!

More people around the world are accessing the information in the Internet using their mobile phones. Asia has the highest population growth in the world. In just a few years' time, it is expected that countries such as China, Indonesia, India, and Pakistan will see the highest growth rate in mobile phone usage.

LINK

Recall the traditional seven colours of visible light that you have learnt in Chapter 12.

PHYSICS WATCH

Scan this page to watch a clip of an experiment on searching for invisible electromagnetic waves.

13.1 Electromagnetic Spectrum

In this section, you will learn the following:

- Know the main regions of the electromagnetic spectrum in order of frequency and wavelength.
- Know that all electromagnetic waves travel at the same high speed in a vacuum.

What light is invisible?

You have learnt in Chapter 12 that sunlight produces a spectrum of colours when passed through a prism. These colours are part of visible light that can be seen by the human eye.

Suppose you place thermometers to measure the temperature of different parts of the visible spectrum and beyond (Figure 13.1). What do you think you will observe?

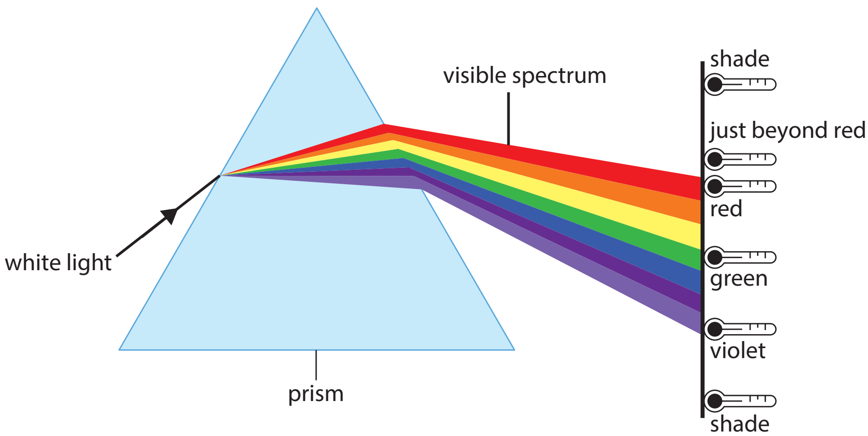


Figure 13.1 *Will the temperature just beyond the red be the same as in the shade?*

WORD ALERT

Invisible: cannot be seen

The astronomer Sir Frederick William Herschel did the above experiment. His experiment showed that there are some parts of the spectrum just beyond the red that are invisible to our eyes (Figure 13.2).

As it turns out, later scientists learnt that the spectrum of light from the Sun consists of more than the colours of light that we can see. There are invisible parts that can only be detected by instruments.

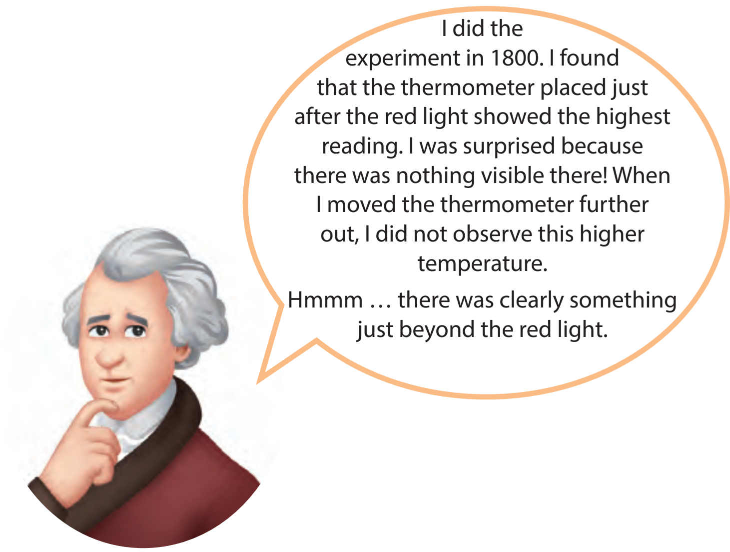


Figure 13.2 *Sir Frederick William Herschel*

What are the main regions of an electromagnetic spectrum?

Light from the Sun travels as electromagnetic waves. These waves are of different types and they make up the **electromagnetic spectrum**. Our eyes can only detect the visible light waves which is only a small part of the spectrum. Other waves include radio waves, microwaves, infrared radiation, ultraviolet radiation, X-rays and gamma rays. Some of these waves can be generated using electricity.

Figure 13.3 shows the main regions of the electromagnetic waves.

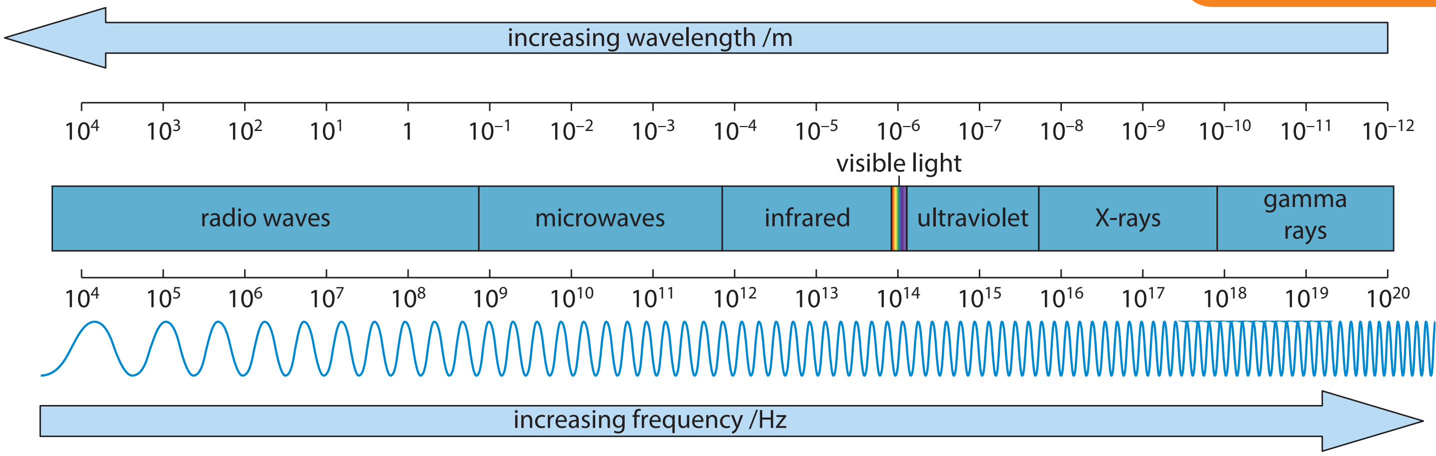


Figure 13.3 *Main regions of the electromagnetic spectrum in order of frequency (increasing from left to right) and wavelength (increasing from right to left)*

Each type of electromagnetic wave has different ranges of wavelengths and frequencies. For example, visible light ranges from violet with the shortest wavelength to red with the longest wavelength.

Electromagnetic waves travel at high speed in a vacuum

Look at Figure 13.3. What do you notice about the wavelength and frequency?

Waves with higher wavelength have lower frequencies. Recall the equation for wave speed and see the **inverse** relationship between wavelength λ and frequency f:

$v = f \times \lambda$

$\therefore \lambda = \frac{v}{f}$

All electromagnetic waves travel at the **same high speed** in a vacuum.

Infrared, visible light, ultraviolet and all the other electromagnetic waves travel from the Sun to the Earth with the same high speed. This is also true for electromagnetic waves coming from faraway stars and galaxies, i.e., they travel with the same high speed.

Let's Practise 13.1

1 Which region of the electromagnetic spectrum has
(a) the shortest wavelengths; **(b)** the longest wavelengths?

2 Which region of the electromagnetic spectrum has
(a) the lowest frequencies; **(b)** the highest frequencies?

3 Arrange regions of the electromagnetic spectrum according to wavelengths from the highest to the lowest.
visible light, microwaves, infrared, gamma rays, ultraviolet, X-rays, radio waves

4 The speed of radio waves from far away stars is smaller than the speed of visible light from the Sun. True of false? Explain your answer.

5 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

HELPFUL NOTES

To recall electromagnetic waves in order of frequency (or wavelength), remember this line:

Rugby (Radio waves)
Match (Microwaves)
Is (Infrared)
Very (Visible light)
Unlike (Ultraviolet)
Xylophone (X-rays)
Game (Gamma rays)

WORD ALERT

Inverse: opposite effect (in this case, when one variable increases, the other decreases)

LINK

Exercise 13A, pp. XX–XX

13.2 Electromagnetic Radiation

In this section, you will learn to:
- Describe some uses of the different regions of the electromagnetic spectrum.
- Describe some harmful effects of electromagnetic radiation.
- Know that communication with artificial satellites is mainly by microwaves.

What is electromagnetic radiation?

Electromagnetic waves transfer energy as they move. The term *radiation* is usually used to refer to the energy being transferred. The energy carried by electromagnetic radiation depends on the frequencies. Higher frequency radiation has more energy for the same intensity of radiation. The different types of electromagnetic radiation have different uses and harmful effects.

What are some uses of electromagnetic radiation?

Figure 13.4 shows some uses of electromagnetic radiation.

Uses of Electromagnetic Radiation

Gamma rays
- They are produced when radioactive nuclei decay. (You will learn more about radioactivity and gamma rays in Chapter 20.)
- They can kill living organisms such as bacteria, and are therefore used to *sterilise food and medical equipment*.
- They can be used to *treat cancer* by destroying cancer cells. Gamma rays can penetrate body tissues. Very small amount of radioactive chemicals that emit gamma rays can be placed inside specific body parts. A gamma camera outside the body captures images that show the inside of the human body. Such images can be used to *detect cancer*.

X-rays
- They can penetrate soft tissues in the human body but are blocked by bones and tumours. They are useful for *medical scanning*.
- Their ability to pass through most materials make them useful as *security scanners* to locate hidden weapons. The metal in guns and knives absorbs the X-rays. Baggage scanners at airports use X-rays.

Ultraviolet light
- It has frequencies just above the higher end of visible light. Although we cannot see ultraviolet light, what we see is the violet-blue end of the visible spectrum. However, some animals such as birds can detect ultraviolet light.
- It can damage the cells of microorganisms. So, it can be used *to sterilise water and other objects* such as a mobile phone.
- Some chemicals that appear transparent can be made to glow under ultraviolet light. This fact is used to make invisible *security marking* and *for detecting fake banknotes*.

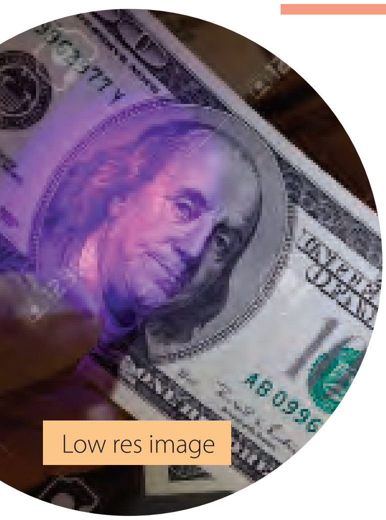


Figure 13.4 *Some uses of electromagnetic radiation*

Visible light

- It consists of wavelengths that can be detected by our eyes.
- We rely on this light for *vision* and *illumination*.
- In *photography*, sensors that are sensitive to visible light are used in cameras for taking photographs.

Microwaves

- They have wavelengths that are longer than infrared.
- They cause water molecules in food to vibrate and heat up quickly. This effect is used in *microwave ovens* for cooking.
- Some microwaves can penetrate clouds. Artificial satellites high above the Earth receive and retransmit microwave signals. These signals from the satellites carry image and sound data which can be received by the antenna of a satellite television. Direct broadcast television, on the other hand, uses geostationary satellites to beam the television signals directly to homes.
- *Satellite phones* can receive microwave signals from geostationary satellites, which are about 36 000 km above the equator. Due to the great distance, the signals are not very strong. So some satellite phones use signals from low Earth orbit (LEO) satellites, which are at about 1500 km above the Earth.
- A *mobile (cell) phone* convert sound energy to microwave signals. The microwaves are sent out to the nearest cell tower. The receiver on the mobile phone converts the microwaves back to sound.

Infrared light

- It has wavelengths longer than red light.
- It causes heating and is used to generate heat. Some people use infrared lamps for *warmth* or for *pain relief*.
- An *electric grill* converts electrical energy to infrared, which is used to heat and cook food.
- In *thermal imaging*, thermal scanners have detectors that convert infrared to electrical signals. These electrical signals are in turn converted into thermal images. Thermal images use colours to display the temperatures of objects.
- Infrared can be easily generated and detected. This is used in *short-range communications*. For example, a simple LED (light emitting diode) is the infrared source for the television remote controller.
- An infrared transmitter and detector can be used to *detect intruders*. The alarm will sound when the direct path between the transmitter and detector is blocked.
- Like visible light, some infrared can pass through glass. When used in *optical fibres*, infrared signals can transmit data over long distances with minimal loss in signal strength.

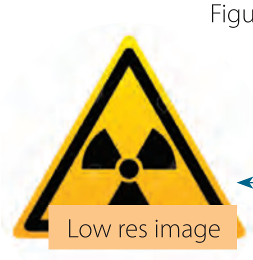
Radio waves

- They have the lowest frequencies and the lowest energies.
- They are used in *radio and television transmissions*. Tall broadcast towers send radio waves out into the air. The radio waves are converted to sound in radios, and to sound and images in televisions. Having long wavelengths (as long as 1 km and longer), radio waves can diffract around most objects such as buildings and hills, and can pass through walls. In order for radio waves to travel very far (e.g. across oceans), the broadcast signals have to be very strong.
- In *astronomy*, large radio telescopes detect radio waves emitted by astronomical objects far out in space. This enables astronomers to learn about stars, comets and galaxies.
- In radio frequency identification (RFID), radio waves are used to transfer data for tracking. Items are given RFID tags that contain data. The data can be read by an RFID reader to track and identify the items.

What are some harmful effects of electromagnetic radiation?

Figure 13.5 shows some harmful effects of electromagnetic radiation.

Harmful Effects of Electromagnetic Radiation



Infrared radiation

- Excessive exposure to infrared radiation can cause *skin burns*.

Microwaves

- Excessive exposure to microwaves can cause *internal heating of body cells*.

X-rays

- They can damage body cells.
- Excessive exposure to X-rays can cause *cancer*.

Ultraviolet radiation

- It is the invisible part of sunlight that cause *damage to the surface cells in our skin and eyes*.
- Excessive exposure to ultraviolet radiation can cause skin cancer and eye conditions such as cataracts and macular degeneration. Remember not to stare at the UV sterilising lamp to avoid damaging your eyes.

Gamma rays

- They can harm living cells.
- The human body must be shielded from gamma rays to protect against *damage to body cells*.

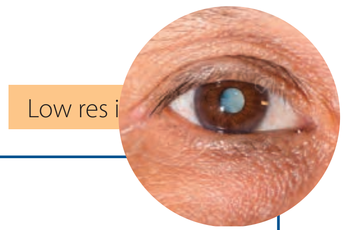


Figure 13.5 *Some harmful effects of electromagnetic radiation*

Let's Practise 13.2

1 **(a)** Complete Table 13.1 by filling in one typical use and one harmful effect due to excessive exposure for each electromagnetic radiation.

Table 13.1

Electromagnetic radiation	Typical use	Harmful effect to our body from over exposure
Infrared		
Ultraviolet		
Microwaves		
X-rays		
Gamma rays		

(b) What regions of the electromagnetic spectrum are missing from the table? What are their typical uses?

2 Which part of the electromagnetic spectrum is usually used to communicate with artificial satellites?

3 For each of the following, state **one** use in communication:

(a) Geostationary satellites

(b) Low Earth orbit satellites

4 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB
Exercise 13B, pp. XX–XX

13.3 Electromagnetic Radiation in Communication

In this section, you will learn the following:
- Know how fast electromagnetic waves travel in a vacuum/air.
- Know that many important systems of communications, such as mobile phones, wireless Internet, Bluetooth and optical fibres, rely on electromagnetic radiation.
- Know the difference between a digital signal and an analogue signal.
- Know that a sound can be transmitted as a digital or an analogue signal.
- Explain the benefits of digital signaling.

What do remote controllers, optical fibres, mobile phones, wireless Internet and Bluetooth have in common? They are important parts of the communication systems that we have today. They all rely on electromagnetic radiation, which enables fast communication.

How fast do electromagnetic waves travel?

All electromagnetic waves travel at the same high speed of **3×10^8 m/s** in a vacuum. They also travel at approximately this same speed in air.

You use a television remote controller to change your television channel. The channel changes immediately when you click the remote controller. The infrared signal (or wave) travels from the remote controller to the receiver on the television at approximately 3×10^8 m/s. It is so fast that we feel the change happening in an instance.

Microwave signals travel to and from our mobile phones at approximately 3×10^8 m/s.
See Worked Example 13A below to find out how long a microwave signal takes to travel over a very long distance.

Worked Example 13A

How long does it take a microwave signal to travel from Earth to a geostationary satellite 36 000 km away and back?

Solution

Total distance = 36 000 km + 36 000 km = 72 000 km or 72×10^6 m

Speed of microwaves in air/vacuum = 3.0×10^8 m/s.

So, time taken for microwave signal to travel = $\dfrac{72 \times 10^6 \text{ m}}{3 \times 10^8 \text{ m/s}} = 0.24$ s

Figure 13.6 A satellite dish transmits microwave signals to a geostationary satellite in outer space.

ENRICHMENT INFO

Looking Back in Time

A supernova is a violent explosion that occurs when a star is dying.

In 1987, astronomers spotted a supernova named SN1987A. The light emitted travelled 1.66 × 1021 m before reaching the Earth.

Using the formula speed = $\dfrac{\text{distance}}{\text{time}}$, we know that the light took about 175 000 years to reach us!

No wonder astronomers say that viewing a supernova is like looking back in time!

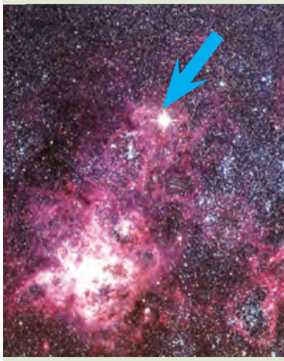


Figure 13.7 Blue arrow pointing to Supernova SN1987A

How do communication systems rely on electromagnetic radiation?

Wireless communication made possible

The invisible radio waves and microwaves allow us to communicate wirelessly — there is no need to use a physical cable to link the transmitter and the receiver.

Microwaves for mobile phones and wireless Internet can pass through some walls. You can use your mobile phone in different rooms of your house. You can use your computer in the bedroom even though your wireless router is in the living room (Figure 13.8).

Figure 13.8 A wireless router in the living room can connect to a computer in the bedroom using microwaves.

You may have seen aerials such as the one shown in Figure 13.9 on the roofs of houses. The rods on the aerial transmit and receive electromagnetic signals of a certain wavelength. To ensure a good reception, the length of the rods needs to be approximately the same size as the wavelength of the signals. The wavelengths of microwaves used in mobile phones are much shorter than radio waves used for television and radio broadcasts. So, by using suitable microwaves, a mobile phone only requires a short aerial for transmission and reception. From the calculation below, we can compare the wavelengths.

Figure 13.9 Different length of rods on this aerial allows it to receive signals of different wavelengths.

To calculate wavelength, use the wave equation $c = f\lambda$. The speed of electromagnetic waves in air c is approximately 3×10^8 m/s.

Radio waves at 90 MHz,

$$\lambda = \frac{3 \times 10^8 \text{ m/s}}{9 \times 10^6 \text{ 1/s}}$$
$$= 3.3 \text{ m}$$

Mobile phone microwaves at 1800 MHz,

$$\lambda = \frac{3 \times 10^8 \text{ m/s}}{1800 \times 10^6 \text{ 1/s}}$$
$$= 0.17 \text{ m or } 17 \text{ cm}$$

Bluetooth technology uses radio waves to allow for wireless connection between two devices. For example, you may connect your mobile phone to a speaker using Bluetooth (Figure 13.10).

Radio waves and microwaves can be weakened as they travel and pass through walls. As a result, you may encounter poor connection when your Bluetooth devices are in different rooms in your house.

Figure 13.10 Two devices can be connected wirelessly over short distances using Bluetooth.

QUICK CHECK

In wireless communication, information is transported without the need of free space.

True or false?

QUICK CHECK

Wireless connection is strongest when the transmitter and the receiver are in view of each other.

True or false?

Optical fibres for long distances and high data rates

Optical fibres are more often being used for cable television and high-speed broadband Internet access. What makes them more advantageous compared to copper wires? Optical fibres are long thin glass fibres that can carry and transmit light over long distances. Visible light undergoes total internal reflection and travels from one end to the other with little loss in energy.

Infrared waves with wavelengths slightly longer than red light can also pass through glass. These infrared waves have shorter wavelengths than other infrared waves. *Optical fibres can transmit both visible light and invisible short wavelength infrared pulses*.

The wavelengths of visible light and infrared used in optical fibres are very short (between 650 nm to 1600 nm). The frequencies of the waves are very high. Many pulses can be transmitted in short time intervals. So, *optical fibres can carry high rates of data*.

What are digital and analogue signals?

Electromagnetic radiation can be used to communicate in two ways: analogue signaling (using analogue signals) and digital signaling (using digital signals).

An **analogue signal** has continuous values in time. The information is transmitted using waves with varying frequencies and amplitudes.

A **digital signal** has fixed values. For example, it can have two values of 1 and 0. The information is transmitted as 'on' and 'off' pulses. The 'on' pulses have a value of 1 and the 'off' pulses have a value of 0.

Figure 13.11 shows graphs of analogue and digital signals.

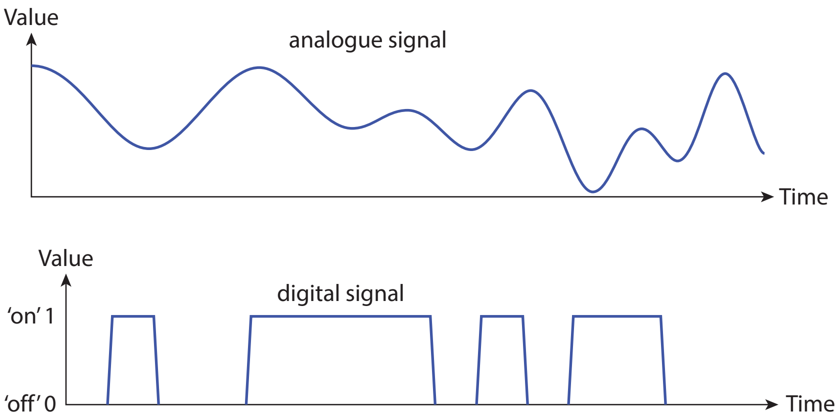


Figure 13.11 *Graphs showing an analogue signal and a digital signal*

Sound can be converted into electrical signals by a microphone. The converted signals are analogue signals. These analogue signals can be encoded and transmitted by radio waves or through a telephone line. However, the analogue sound signals can also be further converted into digital signals before transmission. This is the preferred method of transmission.

When you speak into a mobile phone, your continuous sound signals are converted into digital signals. The phone encodes these digital signals and transmits the signals as microwaves.

LINK

Recall how data is transmitted through optical fibres by total internal reflection. You have learnt this in Chapter 12.

HELPFUL NOTES

Within the electromagnetic spectrum, short wavelength infrared occurs just beyond the red light.

ENRICHMENT
THINK

Figure 13.12 shows an analogue clock. Explain how the clock is similar to analogue signals?

Figure 13.12 *Analogue clock*

WORD ALERT

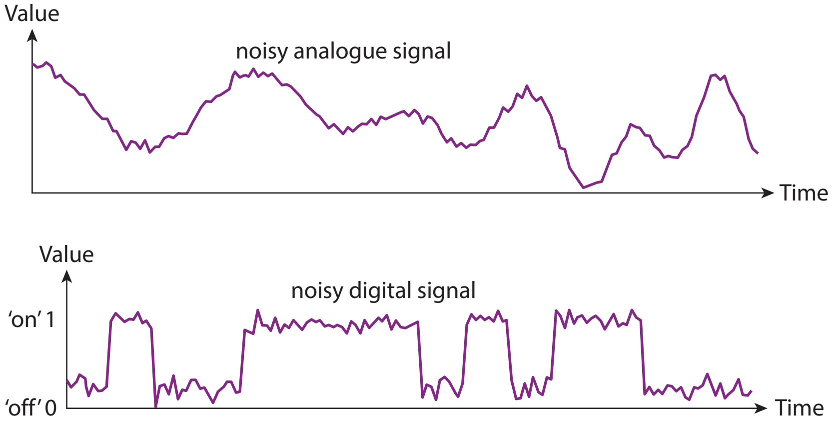
Encoded: convert into another form using symbols

What are the benefits of digital signals?

Digital signals can be represented as numbers, which can be added and multiplied. Using mathematics, these numbers can be transformed and later recovered by processors.

The transformed data take less numbers to encode the same information. This means more data can be transmitted and the rate of data transmission is increased. Since more information can be carried, video and sound transmitted digitally have higher quality compared to when they are transmitted using analogue signals.

When signals are transmitted, two unwanted effects take place: *noise* and *loss in power*. Noisy signals are not very smooth as shown by the graphs (Figure 13.13).



Compare the graph of this noisy digital signal to the graph of the digital signal in Figure 13.11. The 'on' and 'off' values of a noisy digital signal can still be distinguished.

Figure 13.13 *Graphs showing a noisy analogue signal and a noisy digital signal*

For digital signals, only 'on' and 'off' (e.g. 1's and 0's) values are expected. So, if the noise is not too big, the signals can be regenerated accurately. This is especially important when signals are transmitted over long distances because signals lose power. Amplifiers are used to increase the strength of analogue signals. However, in the process, noise is also increased. The result is poor quality signals. For digital signals, repeaters are used along the transmission path. Repeaters recover the digital signal and retransmit it. In this way, digital signals can be accurately regenerated and transmitted over very long distances.

WORD ALERT

Regenerated: created again, reproduce

ENRICHMENT *ACTIVITY*

Do a survey on electronic devices in your home. Make a list of devices that use analogue signals and those that use digital signals.

Share your list with the class.

LINK TWB

Exercises 13C–13D, pp. XX–XX

Exercise 13E Let's Reflect, p. XX

Let's Practise 13.3

1. For each of the following, state its speed of travel in air:
   (a) radio waves; **(b)** gamma rays; **(c)** ultraviolet; **(d)** infrared.
2. State **two** properties of microwaves that are important for their use in mobile phones.
3. Which regions of the electromagnetic spectrum are used in optical fibres? Why?
4. Compare a digital signal and an analogue signal. How are they different?
5. State **two** benefits of digital signaling.
6. **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

Let's Map It

ELECTROMAGNETIC SPECTRUM

consists of the following main regions

- Radio waves
- Microwaves
- Infrared radiation
- Visible light
- Ultraviolet radiation
- X-rays
- Gamma rays

Increasing f

Increasing λ

with the following common property

All electromagnetic waves travel at the same high speed in a vacuum.

S The speed of electromagnetic waves in a vacuum is 3.0×10^8 m/s and is approximately the same in air.

has

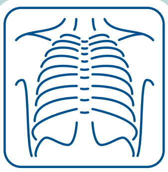
Harmful effects

- Damage to body cells leading to cancer
- Damage to eyes
- Skin burns

has

Uses

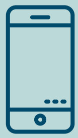
- In medical field: sterilisation, medical diagnosis, scanning, treatment
- In communications: radio and TV transmissions, remote controllers, optical fibres, mobile phones
- In security: security marking, baggage scanners, detection of fake notes
- In other applications: heating, cooking, thermal imaging, photography



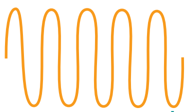
relied upon by

S Communication systems

- Involve the use of mobile phones, wireless Internet, Bluetooth and optical fibres



transmit signals in two forms



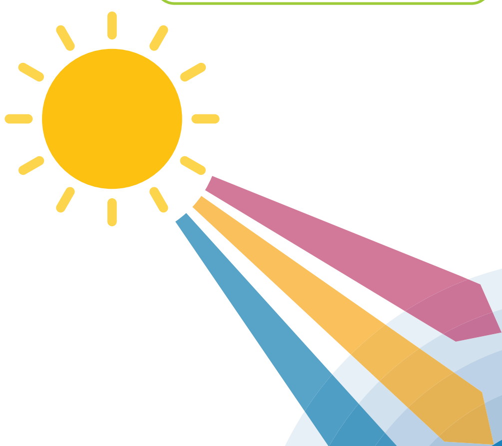
S Analogue signals

- Have continuous values

S Digital signals

- Have fixed values

- S Increased rate of transmission of data
- S Increased range of transmission



Let's Review

Section A: Multiple-choice Questions

1 Which statement about electromagnetic waves is correct?
- **A** All electromagnetic waves are harmful to people.
- **B** All electromagnetic waves have the same wavelengths.
- **C** In vacuum, all electromagnetic waves travel at the same high speed.
- **D** In vacuum, visible light travels faster than all the other electromagnetic waves.

2 Which of the following regions of electromagnetic spectrum can be used to cook food?
- **A** Infrared only
- **B** Microwave only
- **C** Infrared and microwave only
- **D** No region can be used

3 Which region of the electromagnetic spectrum is used to communicate with artificial satellites?
- **A** Radio waves
- **B** Microwaves
- **C** Infrared
- **D** Visible light

4 A lamp is used to sterilise water in an aquarium. What light is used?
- **A** Infrared
- **B** Red light
- **C** Green light
- **D** Ultraviolet

5 S Which statement about microwaves is correct?
- **A** Microwaves travel at approximately 3×10^8 m/s in air.
- **B** Microwaves are not used to communicate with satellites because they are blocked by clouds.
- **C** The wavelengths of microwaves are shorter than visible light.
- **D** The frequencies of microwaves are lower than radio waves.

6 S Which statement about optical fibres is correct?
- **A** Optical fibres carry microwave signals.
- **B** Optical fibres cannot be used to transmit television signals.
- **C** Only visible light is used in optical fibres because only visible light can undergo total internal reflection.
- **D** Visible light and infrared are used because glass is transparent to these waves.

Section B: Short-answer and Structured Questions

1 Figure 13.14 shows the regions in the electromagnetic spectrum.

radio waves	microwaves	A	visible light	B	X-rays	C

increasing D

Figure 13.14

- **(a)** State what each of the labels A, B, C and D represents.
- **(b)** What could happen to someone who is excessively exposed to B?
- **(c)** Describe one use for the waves in region C.

2 To determine the distance of the Moon from the Earth, the time taken for a radio wave signal to travel from the Earth to the Moon and back is 2.5 s.

Given that the speed and frequency of the radio waves are 3.0×10^8 m/s and 10 MHz respectively, calculate the
- **(a)** distance of the Moon from the Earth;
- **(b)** wavelength of the radio waves used.

3 S Figure 13.15 shows two signals corrupted by noise.

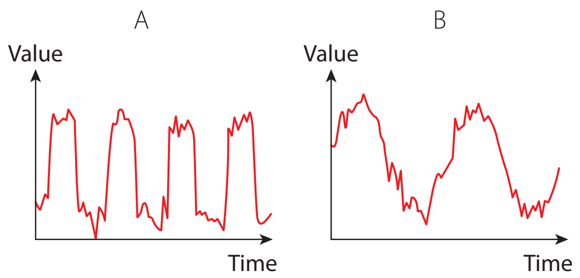


Figure 13.15

- **(a)** Which signal, A or B, is a digital signal?
- **(b)** Explain the benefits of digital signaling.

CHAPTER

14 Sound

Have you watched any of the Star Wars movies or one that is similar to it? If you have, you would probably find the battle scenes in space most thrilling. The scenes are made exciting with dazzling sights and sounds. But, can we hear sound in outer space? The answer is 'No'. Movie producers ignore this law of physics and go for 'effects'.

Often, there is a misconception about sound in space. This is mostly due to the sound effects used in sci-fi movies.

PHYSICS WATCH

Scan this page to watch a clip about how sound travels.

QUESTIONS

- Imagine a battle scene taking place on Earth. What sounds would you expect to hear and why would you be able to hear these sounds?
- What misconception about sound in space do people have?
- Why do you think we cannot hear sound in space?

14.1 What Is Sound?

In this section, you will learn the following:
- Describe the production of sound by vibrating sources.
- Describe the longitudinal nature of sound waves.
- S Describe *compression* and *rarefaction*.
- State the approximate range of frequencies audible to humans.

LINK

Recall the characteristics of longitudinal waves that you have learnt in Chapter 11.

Sound is a form of energy that is transferred from one point to another.

Since sound is a type of wave. It has amplitude, frequency and wavelength. *Sound waves travel parallel to the direction of vibration of a medium*. Therefore, sound waves are *longitudinal waves.*

How is sound produced?

PHYSICS WATCH

Scan this page to watch an experiment on producing sound.

How do guitar players produce sounds from their guitars? They strike the guitar strings causing the strings to vibrate. Sometimes, guitar players place their palms on the strings. This mutes the guitar because it stops the guitar strings from vibrating.

Sound is produced by **vibrating sources** placed in a medium. The medium is usually air, but it can be any gas, liquid or solid.

How does a sound wave propagate?

An object vibrating in air causes the layers of air particles around it to be displaced. This displacement of particles causes sound waves to propagate. We cannot see the displacement of air particles. However, if we dip a vibrating tuning fork in water, we will see that the water is displaced (Figure 14.1).

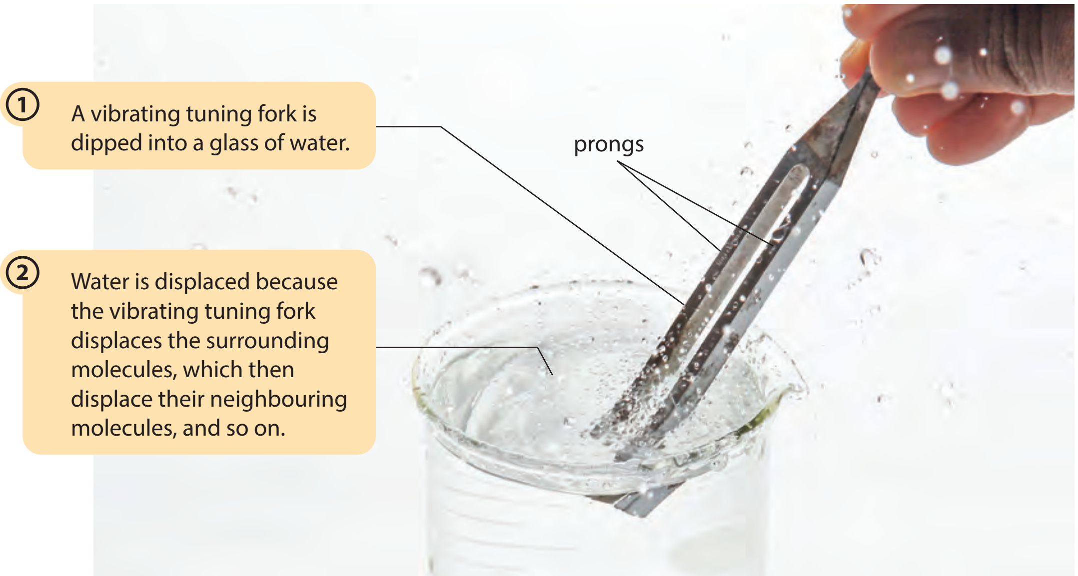


Figure 14.1 *A vibrating object displaces the particles in a medium.*

ENRICHMENT ACTIVITY

Use your mouth and try to produce the sound /s/ (as in the hissing sound of a snake). While doing that, place your thumb and your index and middle fingers near the middle of your throat. Do you feel any vibrations of your vocal cords?

Repeat the above while producing another sound /z/ (as in the buzzing of a bee). What do you notice this time?

Share your observations with your classmates.

As sound is a longitudinal wave, the direction of vibration of air molecules is parallel to the direction in which the wave travels. This is similar to the longitudinal waves produced when a Slinky spring is made to vibrate parallel to its length (Figure 14.2).

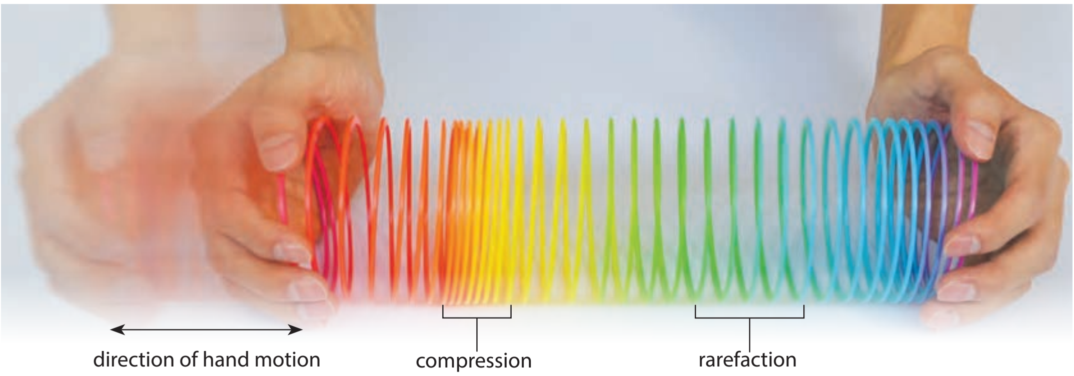
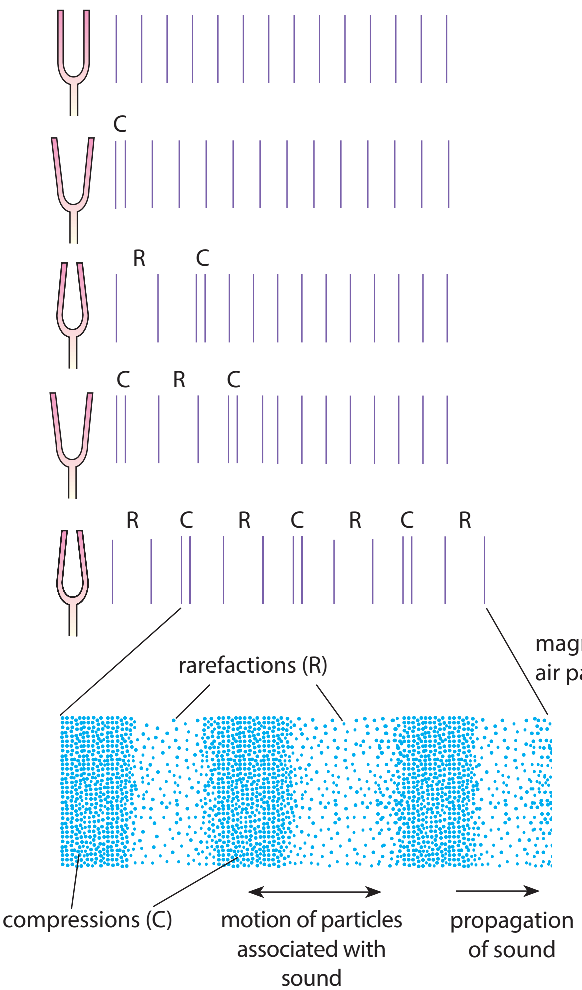


Figure 14.2 *Longitudinal wave in a Slinky spring*

Like all longitudinal waves, sound waves propagate as a series of *compressions* (C) and *rarefactions* (R).

- **Compressions** are regions where air pressure is higher than the surrounding air pressure.
- **Rarefactions** are regions where air pressure is lower than the surrounding air pressure.

Figure 14.3 shows how sound waves are produced by a vibrating tuning fork.



1. Layers of air are in undisturbed positions.
2. A compression (C) is produced as the prongs push outward.
3. A rarefaction (R) is produced as the prongs move inward.
4. Another compression (C) is created as the prongs move outward again.
5. After a while, a series of C and R is set up in the air.

Figure 14.3 *As a tuning fork vibrates, it shifts layers of air inward and outward, creating a series of compressions and rarefactions*

QUICK CHECK

There are less air particles in a region of compression than in a region of rarefaction.

True or false?

WORD ALERT

Audible: can be heard

What sounds are audible?

We can only hear sounds that are audible to us. The human ear is only capable of detecting sounds in a certain range of frequencies. The range of frequencies in which a person can hear is known as the *range of audibility*. For humans, this range is from **20 Hz to 20 000 Hz**.

The top and bottom values of the range are known as the *limits of audibility*. For the human ear, the lower limit is about 20 Hz and the upper limit is about 20 000 Hz.

Figure 14.4 shows examples of the range of audibility and the range of frequency of sounds.

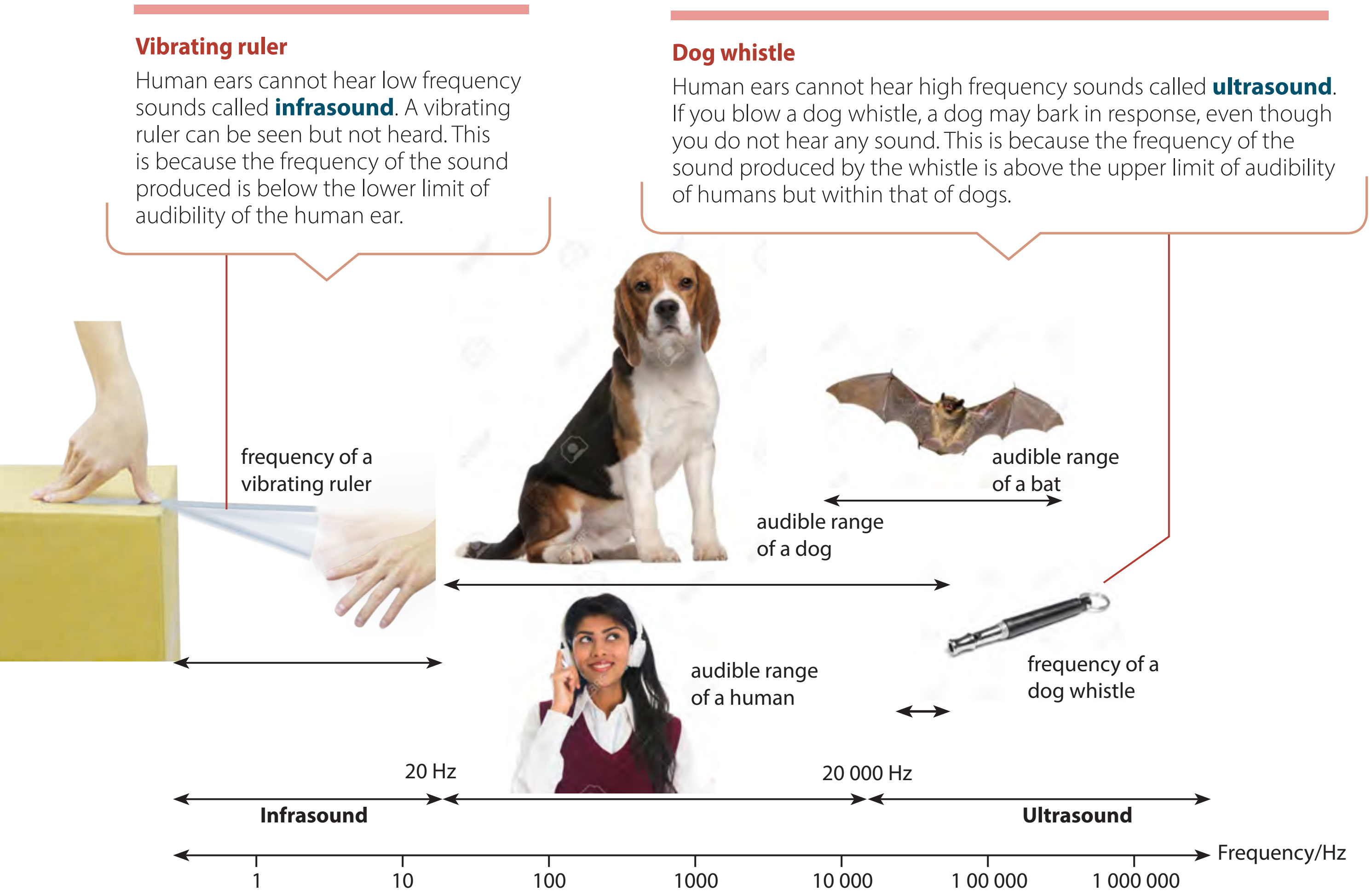


Figure 14.4 Spectrum of sound frequencies

Let's Practise 14.1

1. Read each sentence and state the meaning of each underlined term.
   (a) *Sound is a <u>longitudinal wave</u>.*
   (b) S *Sound is transmitted as a series of <u>compressions</u> and <u>rarefactions</u> in air.*
2. A vibrating source produces ultrasound at a frequency of 40 kHz. Is this frequency within the audible range of the human ear? Give your reason.
3. **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

Exercise 14A, pp. XX–XX

14.2 Transmission of Sound

In this section, you will learn the following:

- Know that a medium is needed to transmit sound waves.
- Know that the speed of sound in air is approximately 330–350 m/s.
- S Know that, in general, sound travels faster in solids than in liquids and faster in liquids than in gases.
- Describe a method involving a measurement of distance and time for determining the speed of sound in air.

Can sound be transmitted through a vacuum?

Unlike electromagnetic waves, *sound waves need a medium to travel* from one point to another. The bell jar experiment demonstrates this (Figure 14.5).

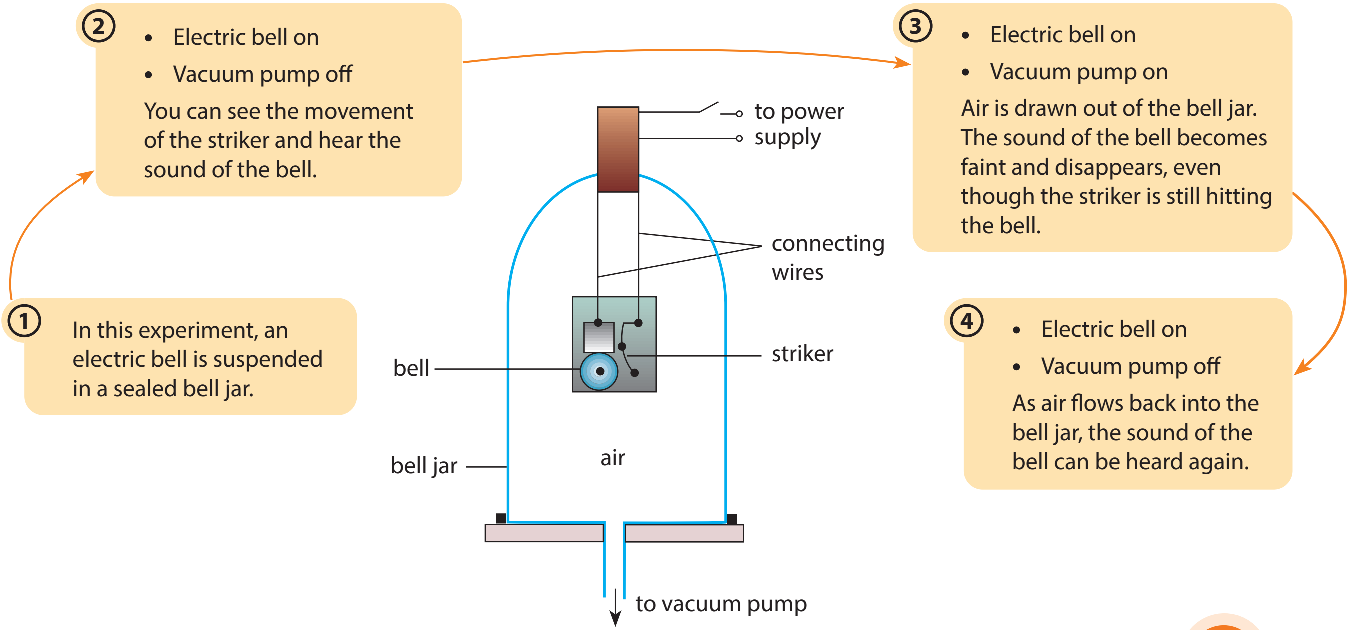


Figure 14.5 *The bell jar experiment shows that sound cannot travel through a vacuum.*

QUICK CHECK

We can hear sound in a vacuum.

True or false?

S Medium of transmission

Any medium which contains particles that can vibrate will transmit sound. However, sound waves travel at different speeds in different media:

speed of sound in gas < speed of sound in liquid < speed of sound in solid

Table 14.1 shows the approximate speed of sound in different media.

Table 14.1 *Speeds of sound in different media*

Medium	Air	Water	Iron	Granite
Approximate speed of sound/m/s	300	1500	5000	5400

How can we measure the speed of sound in air?

Let's Investigate 14A demonstrates one method of measuring the speed of sound in air. This method involves the measurement of distance and time.

Let's Investigate 14A

Objective
To measure the speed of sound in air by a direct method

Apparatus
Electronic starting pistol with light flash, stopwatch, measuring tape

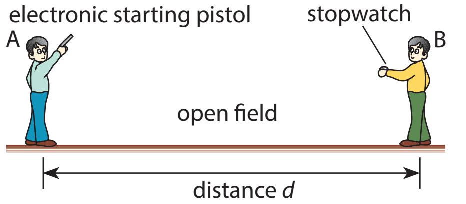


Figure 14.6

Procedure

1 Using a measuring tape, observers A and B are positioned at a known distance *d* apart in an open field (Figure 14.6).
2 Observer A fires an electronic starting pistol.
3 On seeing the flash of the starting pistol, observer B starts the stopwatch and then stops it when he hears the sound. The time interval *t* is then recorded.

Results and discussion
A typical set of data: $d = 800$ m, $t = 2.4$ s

$$\text{The speed of sound in air } v = \frac{\text{distance } d \text{ travelled by sound}}{\text{time taken } t}$$

$$= \frac{800 \text{ m}}{2.4 \text{ s}}$$

$$= 333 \text{ m/s}$$

The accuracy of the speed of sound in air *v* can be increased in two ways:

1 Repeat the experiment a few times, and calculate the average value of the speed of sound in air. Taking the average minimises the random errors that may occur while timing the interval.
2 Repeat the experiment but with the positions of observers A and B interchanged. This cancels the effect of wind on the speed of sound in air.

LINK PWB
Practical 14,
pp. XX–XX

Let's Practise 14.2

1 Can sound travel directly from one spaceship to another one nearby? Why?
2 A woman standing 1.00 km away from a storm hears the sound of thunder 3 s after she sees a flash of lightning. Calculate the speed of sound in air in m/s.
3 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB
Exercise 14B,
pp. XX–XX

14.3 Echoes and Ultrasound

In this section, you will learn the following:
- Describe an echo as the reflection of sound waves.
- Define ultrasound as sound with a frequency higher than 20 kHz.
- S Describe the uses of ultrasound.

Echoes

What is an echo?

Figure 14.7 illustrates what an echo is.

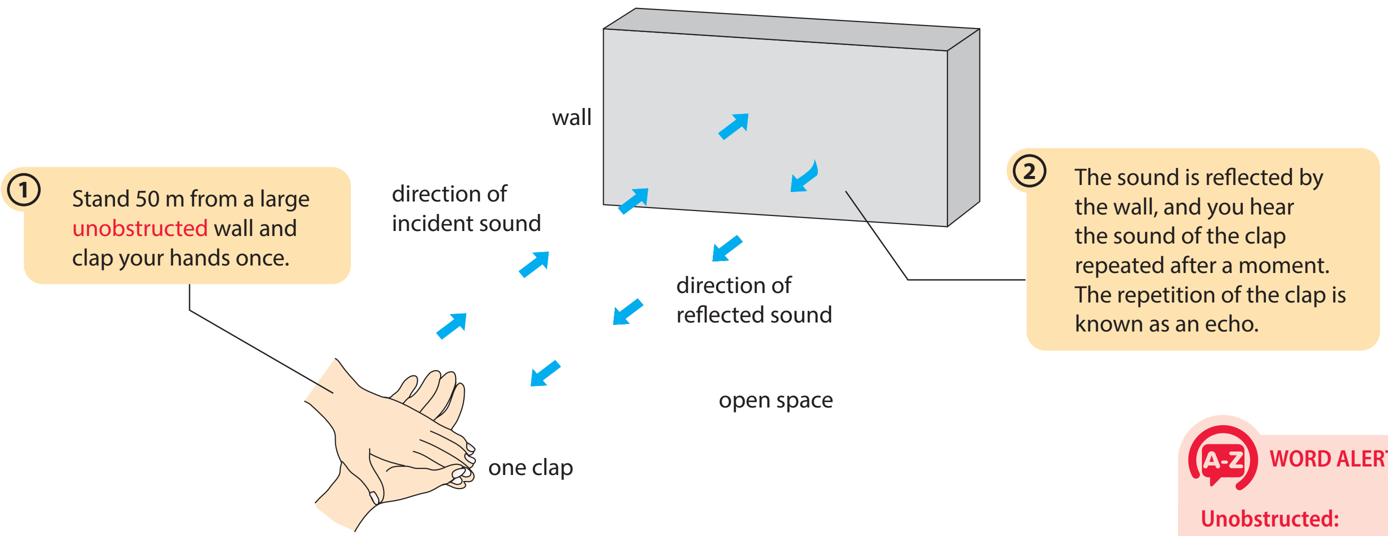


Figure 14.7 *Forming a single echo*

WORD ALERT

Unobstructed: not blocked

An **echo** is a reflection of sound waves.

How are echoes formed?

An echo is formed when a sound is reflected off hard, flat surfaces, such as a large wall or a distant cliff. The law of reflection of light also applies to sound waves. Figure 14.8 shows a simple experiment to illustrate the reflection of sound.

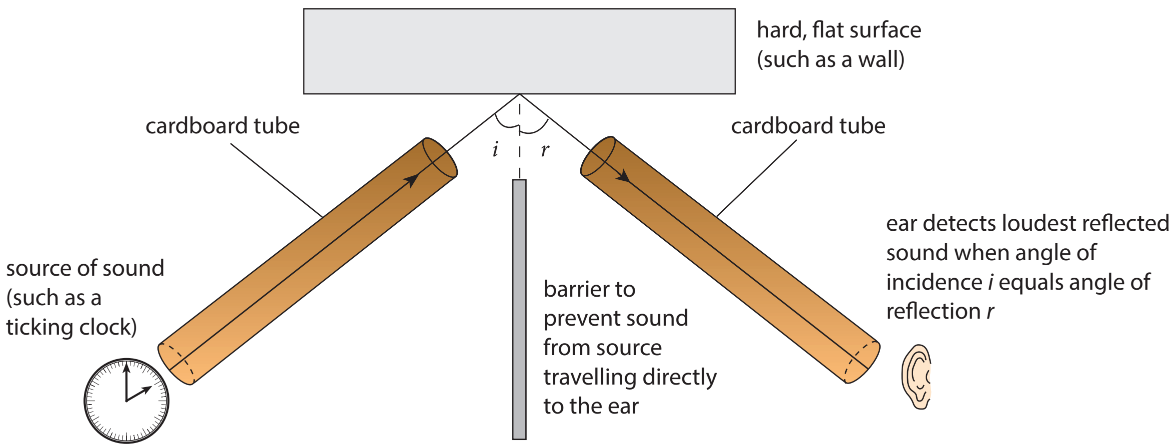


Figure 14.8 *Sound reflected off a surface*

HELPFUL NOTES

The word *sonar* is an acronym for the term ***s**ound **n**avigation **a**nd **r**anging*.

WORD ALERT

Cavities: holes or gaps

Foetuses: unborn babies

Ultrasound

What is ultrasound?

Ultrasound is sound with a frequency higher than 20 kHz.

In other words, ultrasonic frequencies are frequencies above the upper limit of the human range. Ultrasound has many uses. Bats and dolphins use ultrasound in echolocation (i.e. detecting the location of objects using echoes). Most sonar technologies also use ultrasound.

What are the uses of ultrasound?

Testing materials for quality control

Manufacturers of concrete use ultrasound to check for cracks or cavities in concrete slabs (Figure 14.9). Ultrasound can also be used to inspect metal pipes and measure the thickness of wooden boards.

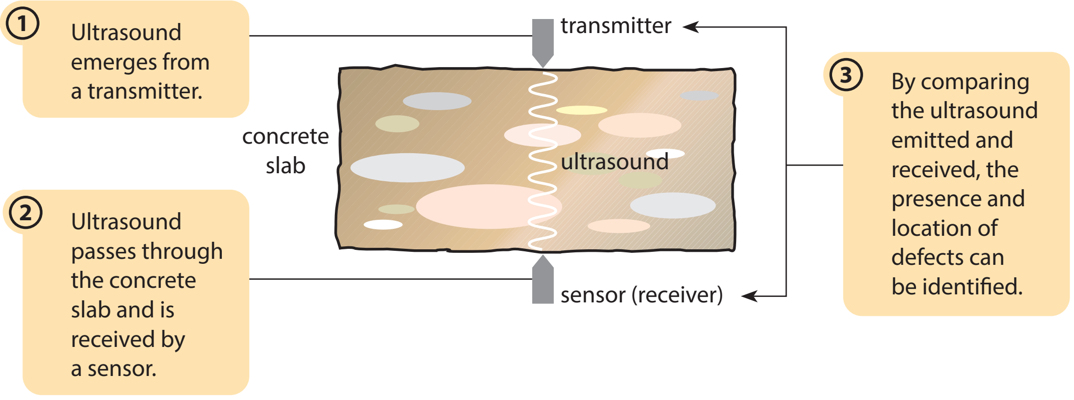


Figure 14.9 *Inspecting a concrete slab using ultrasound*

Medical scanning

Ultrasound can be used to obtain images of structures in the body. It is commonly used to examine the development of foetuses (Figure 14.10). Ultrasound is used instead of X-rays because it is less hazardous due to its lower energy.

Ultrasound pulses are sent into the womb of a pregnant woman via a transmitter. The time taken for the ultrasound pulses to be reflected is measured. From this, the depth of the reflecting surface within the womb can be derived, and an image is formed.

Figure 14.10 *A doctor scans the womb of a pregnant woman. The monitor shows an ultrasound image of the foetus inside the womb.*

Sonar

Sonar is a type of technology that works based on echolocation. It is used by ships for navigation at sea and to detect the position of other vessels.

For example, we can find the depth of the sea or the position of shoals of fish using sonar. This is done by sending out a signal (a pulse of sound) and noting the time interval before the reflected signal (the echo) arrives (Figure 14.11).

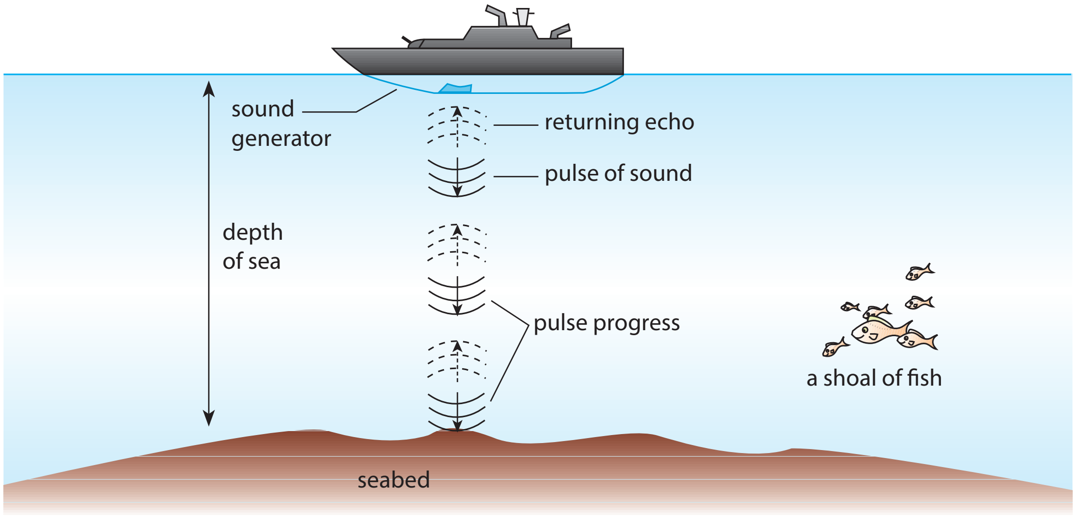


Figure 14.11 *A ship sends out a pulse of sound to determine the depth of the sea.*

Worked Example 14A

A ship uses a sonar as a depth sounder to measure the depth of a seabed. It sends a pulse of sound downwards into the sea. An echo from the seabed is received 0.3 s after the pulse is sent. If the speed of sound in water is 1500 m/s, determine the depth of the sea.

Solution

Given: Time for sound to travel to and back from seabed, $t = 0.3$ s

Speed of sound in water, $v = 1500$ m/s

Using $v = \dfrac{2d}{t}$, where d is the depth of the sea,

we get $d = \dfrac{vt}{2} = \dfrac{1500 \text{ m/s} \times 0.3 \text{ s}}{2} = 225$ m

Let's Practise 14.3

1 A pulse of sound is transmitted from a ship towards the seabed. If the echo is received after 1 s, calculate the depth of the sea, given that the speed of sound in water is 1500 m/s.

2 Why is ultrasound preferred to X-rays for prenatal scanning, although both types of waves can be used to obtain images of internal organs?

3 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

ENRICHMENT INFO

How Do Dolphins Navigate in Water?

Dolphins emit a series of clicks at about 100 kHz through their foreheads and receive the echoes through their lower jaws. From the frequencies and direction of the echoes, dolphins can deduce the nature and location of objects in their paths.

Figure 14.12 *Dolphins navigate underwater using echolocation.*

ENRICHMENT THINK

Some bats use echolocation to help them find their prey in the dark. Others rely more on their sight to find food.

The common Asian ghost bat (Figure 14.13) can be found in South and Southeast Asia. From the photo, how do you think this bat find its food?

What would be an effective way to catch this bat? Explain how your method will work.

Figure 14.13 *Common Asian ghost bat*

LINK

TWB Exercise 14C, pp. XX–XX

14.4 Pitch and Loudness

In this section, you will learn the following:

- Describe how changes in amplitude and frequency affect the loudness and pitch of sound waves.

We experience a great variety of sounds every day. Some sounds are pleasant, whereas some are not. Pitch and loudness are among the characteristics of sound that help us determine whether a sound is pleasant.

QUICK CHECK

The pitch of a sound depends on its frequency.

True or false?

What affects the pitch of a sound?

We often describe sounds as being *high-pitched* or *low-pitched*. Do you know what causes a sound to be high-pitched or low-pitched?

Pitch is related to the frequency of a sound wave — the higher the frequency, the higher the pitch.

Pitch is relative. For example, a 200 Hz sound has a higher pitch compared to a sound of 100 Hz. However, the 200 Hz sound has a lower pitch compared to a sound of 400 Hz.

Two tuning forks of different lengths produce sounds of different pitch (Figure 14.14). This is because the tuning forks generate sound waves of different frequencies.

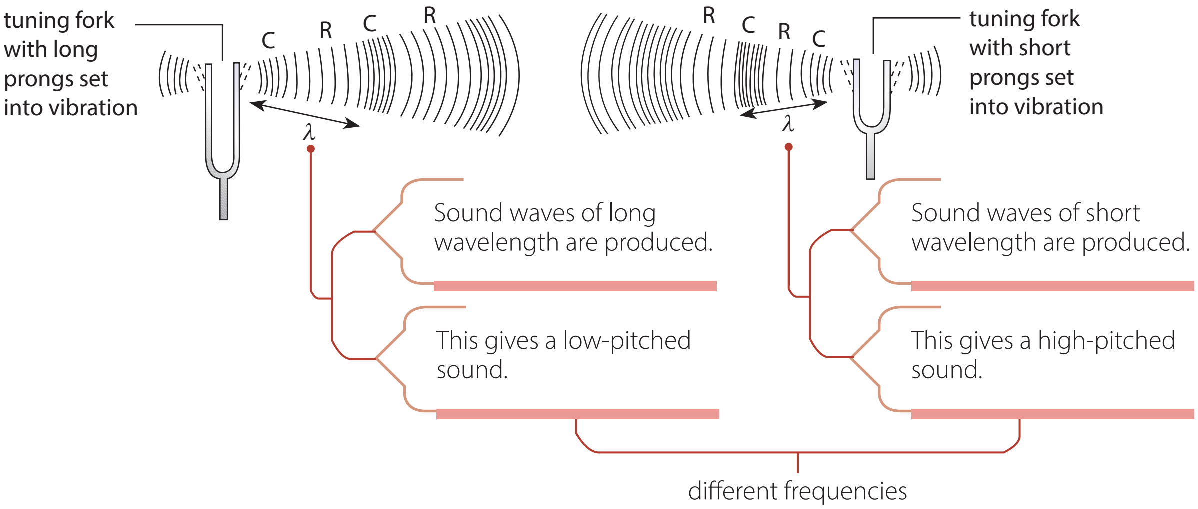


Figure 14.14 *Tuning forks with prongs of different lengths produce sounds of different pitch.*

To observe the waveforms of sound waves, we use a microphone and a cathode-ray oscilloscope (c.r.o.) (Figure 14.15).

① Sound waves are directed to the microphone.

② Sound waves are converted to electrical energy by the microphone.

③ The waveform is displayed on the c.r.o. screen as a displacement–time graph.

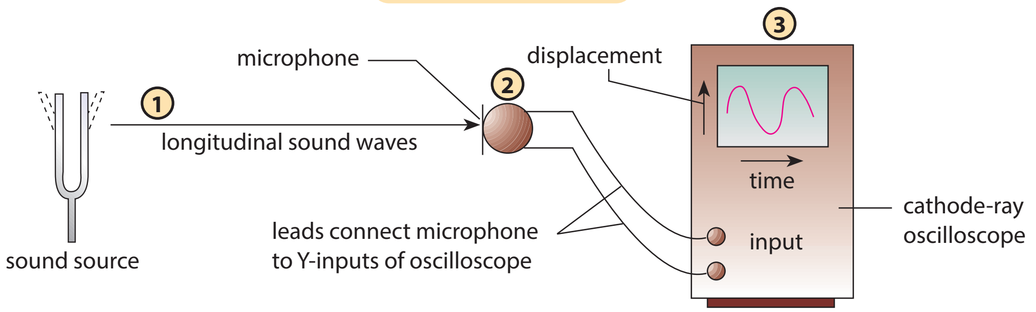


Figure 14.15 *A c.r.o. can be used to visualise sound waves.*

If the sound waves produced by the tuning forks in Figure 14.14 are channelled into a c.r.o., the resulting waveforms will look like the ones shown in Figures 14.16 and 14.17. Note that the same time base is used.

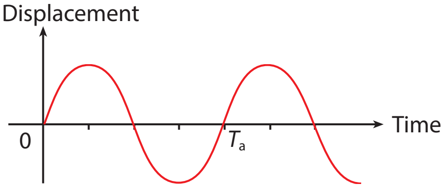


Figure 14.16 *The waveform for the tuning fork with long prongs.*

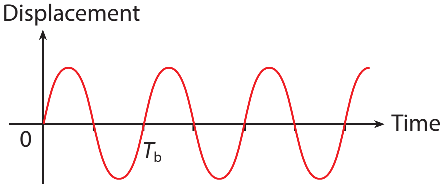


Figure 14.17 *The waveform for the tuning fork with short prongs.*

From Figures 14.16 and 14.17, the period T_a of the long tuning fork is longer than the period T_b of the short tuning fork.

Recall that frequency f is related to period T by the equation $T = \frac{1}{f}$. Since $T_a > T_b$, the frequency $f_a = \frac{1}{T_a}$ of the long tuning fork is lower than the frequency $f_b = \frac{1}{T_b}$ of the short tuning fork. Hence, the tuning fork with long prongs produces a sound with a lower pitch or frequency compared to the tuning fork with short prongs.

What affects the loudness of a sound?

To the human ear, the loudness of a sound is subjective. For a particular volume of sound, some people may find it loud, whereas others may find it soft.

Loudness is related to the amplitude of a sound wave — the larger the amplitude, the louder the sound. Figures 14.19 and 14.20 show two waveforms of the same frequency but with different amplitudes of vibration.

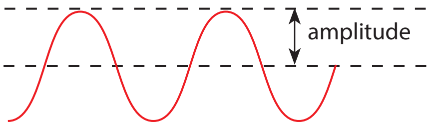


Figure 14.19 *A loud sound has a large wave amplitude.*

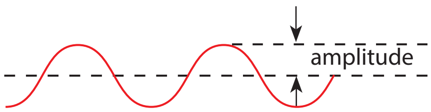


Figure 14.20 *A soft sound has a small wave amplitude.*

Let's Practise 14.4

1. Of these quantities — speed, frequency, wavelength, and amplitude — which is associated with the
   (a) loudness of a sound; **(b)** pitch of a sound?
2. Compare in terms of loudness and pitch the sounds made by a mosquito flying near your ear and the croaking of a bullfrog.
3. **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

ENRICHMENT ACTIVITY

Get several glass bottles of the same size and shape. Fill the bottles with different levels of water. Now, blow across the top of each bottle (Figure 14.18).

Why is there a difference in the pitch of each note?

In groups, try to play a simple song using bottles filled with different levels of water. Record which note each bottle plays. Then, explain how you managed to do this.

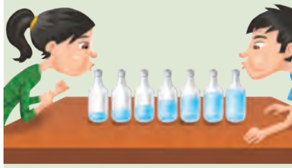


Figure 14.18

LINK

Exercises 14C–14D, pp. XX–XX

Exercise 14E Let's Reflect, p. XX

Let's Map It

SOUND

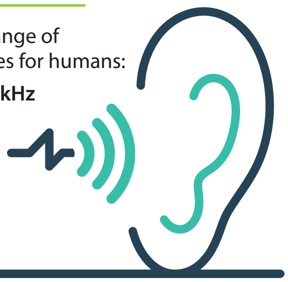
production

Produced by vibrating sources

direction of vibration shows that sound is a

Longitudinal wave
- Air molecules vibrate parallel to the wave motion
- S Transfers energy from one point to another via a series of **compressions** and **rarefactions**

Audible range of frequencies for humans:
20 Hz–20 kHz

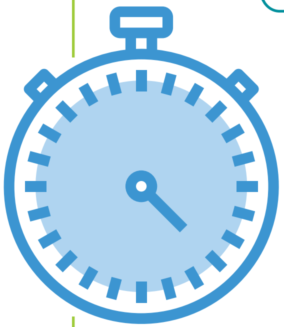


transmission

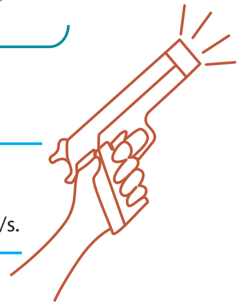
Requires a medium for propagation

- The speed of propagation depends on the medium:

$v_{gas} < v_{liquid} < v_{solid}$



Travels in air at a speed of ~ 330–350 m/s.



Can be determined by using a method involving measurement of distance and time

Can be reflected off a hard surface as **echoes**

Known as **ultrasound** if frequency > 20 kHz

has

S Uses in
- Testing of materials
- Medical scanning
- Sonar

has

Pitch
- is related to the frequency of a sound wave

Loudness
- is related to the amplitude of a sound wave

Let's Review

Section A: Multiple-choice Questions

1 A spaceship with astronauts on board orbits the Moon. The astronauts see an asteroid crashing onto the surface of the Moon. Why do they not hear the explosion caused by the crashing of the asteroid?
- **A** All the sound waves are absorbed by the surface of the Moon.
- **B** The sound waves are reflected from the surface of the spaceship.
- **C** The sound waves are unable to travel from the Moon's surface to the spaceship.
- **D** All the sound waves are absorbed by the surface of the spaceship.

2 Based on the information in Table 14.2, which statement correctly describes the speed of sound?

Table 14.2

Substance	Density/ g/cm^3	Speed of sound/ m/s
Lead	11.3	1200
Iron	7.87	5000
Oxygen	0.001 43	320
Air	0.001 29	330

- **A** The denser the substance, the lower the speed of sound.
- **B** As the density of the substance decreases, the speed of sound decreases.
- **C** The speed of sound is greater in metals than in gases.
- **D** The speed of sound increases as the density of the substance increases.

3 Figure 14.21 shows two boys, A and B, standing in front of a tall building. Both boys are facing the building. When boy A claps his hands once, boy B hears two claps that are 2 s apart.

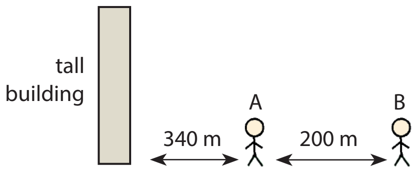


Figure 14.21

Based on the information given, what is the speed of sound in air?

A 300 m/s **B** 340 m/s
C 350 m/s **D** 500 m/s

4 A guitar plays a louder note but at a lower pitch compared to a violin. Which of the following is correct?

	Violin's amplitude	Guitar's frequency
A	Higher	Higher
B	Higher	Lower
C	Lower	Higher
D	Lower	Lower

Section B: Short-answer and Structured Questions

1 A bell is struck by a hammer.
- **(a)** Briefly describe how sound is produced by the bell.
- **(b)** Describe how the sound travels through air to reach the ear of the person striking the bell.

2 In an experiment, a ringing electric bell is suspended inside a bell jar by a thin string. A vacuum pump is then used to draw air out of the bell jar.
- **(a)** When the vacuum pump is not switched on, the ringing of the bell can be heard. When the vacuum pump is switched on, the loudness of the bell decreases until only a very faint sound can be heard. Explain this observation.
- **(b)** Describe and explain what will happen if the electric bell is not suspended by the string but rests on the base supporting the bell jar instead.

3 In an attempt to determine the speed of sound in air, observer A stands 500 m from observer B in an open space. Observer A starts the experiment by firing a flashgun towards the sky. Observer B starts the stopwatch when he sees the flash and stops the stopwatch when he hears the sound of the gun. They repeat the experiment three times and the timings recorded are 1.51 s, 1.55 s and 1.50 s.
- **(a)** Calculate the average speed of sound in air.
- **(b)** Suggest why the observers A and B should not stand 100 m apart for this experiment.

4 S The approximate range of frequencies that the average human ear can detect is 20 Hz to 20 000 Hz.
- **(a)** Dogs can detect ultrasound. Explain what this means.
- **(b)** One application of ultrasound is medical diagnosis, where images of internal body parts are obtained. Describe how ultrasound is used to obtain the images of internal body parts.

Let's Review

5 **(a)** Describe how an echo is formed.

(b) Ⓢ Figure 14.22 shows a ship as it moves from positions A to F above a seabed. At each spot, the ship transmits sound pulses to the seabed to determine its depth profile. The speed of the sound pulses in the seawater is 1500 m/s.

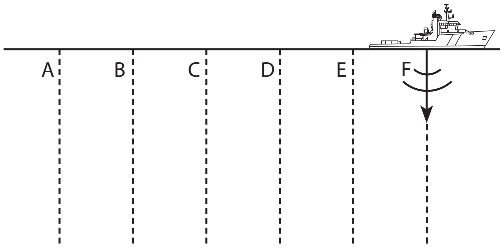


Figure 14.22

Figure 14.23 shows the time interval between each transmitted pulse and the reflected pulse received by the ship. Each thick line represents the transmitted pulse, while each thin line represents the corresponding reflected pulse.

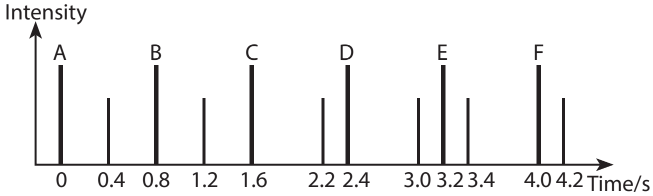


Figure 14.23

(i) Based on the data in Figure 14.23, calculate the depth of the seabed at each of the positions A to F.

(ii) On Figure 14.24, draw the rough depth profile of the seabed. Clearly label the depth of the seabed for each of the positions A to F.

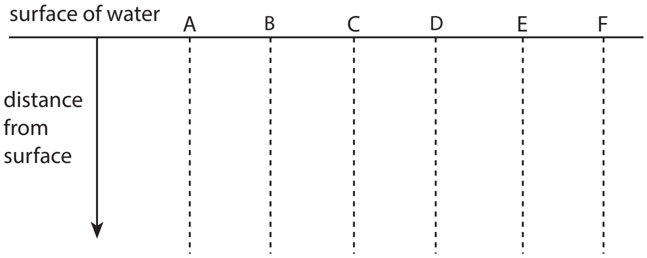


Figure 14.24

(iii) Calculate how long it takes to detect an echo from the seabed if the depth is 60 m.

6 **(a)** Two properties that are used to distinguish one musical sound from another are pitch and loudness. State the physical characteristic of sound waves to which

(i) pitch is related;

(ii) loudness is related.

(b) A student tries to produce notes of higher frequency by blowing a trumpet harder. Discuss whether the student will succeed.

CHAPTER 15 Simple Phenomena of Magnetism

PHYSICS WATCH

Scan this page to watch a clip on how a maglev train works.

This Shanghai Transrapid magnetic levitation (maglev) train is one of the fastest trains in the world. It has a top speed of 431 km/hr! It takes passengers from the airport to the city centre in merely seven minutes. Many passengers take pictures of the speed indicator as it climbs higher and higher.

The train floats above the track using magnets placed on the tracks and under the train. The floating of the train reduces frictional force acting on the wheels, thus allowing it to move at very high speeds and very quietly. To move the train forward, the poles of the magnets can be switched. Compared to burning fuel in a traditional train, the maglev train is a more environmentally-friendly vehicle.

QUESTIONS

- Imagine yourself sitting in a maglev train. Compared to a traditional train, what would be some differences?
- How does an object float?
- What do you think allows the train to float?
- How does floating help the train to move at a very high speed?

15.1 Magnets and Their Properties

In this section, you will learn the following:

- Describe the forces between magnets, and between magnets and magnetic materials.
- State the difference between magnetic and non-magnetic materials.
- Describe induced magnetism.

How were magnets discovered?

Long ago, people observed that special types of stone, known as lodestone (Figure 15.1), attracted iron objects. Around 800 years ago, it was discovered that objects made from lodestone pointed in the same directions when hung freely. Those directions were later known as the North and South poles of the Earth. Due to this property of showing the direction, lodestones are very useful navigation tools.

Lodestone is a naturally occurring magnet. Magnets and magnetic materials are found everywhere. They are used in many applications where two things are required to stick together or push away from each other.

Figure 15.1 *A lodestone attracting iron clips*

LINK

Find out what causes magnets to exert a magnetic force in Section 15.3 of this chapter.

LINK

Recall how forces change the motion of an object in Chapter 4.

LINK

Find out how magnetic materials can be separated from non-magnetic materials in Section 15.2 of this chapter.

What are the properties of magnets?

A magnet is an object that exerts a magnetic force. The magnetic force of a magnet causes it to display certain properties.

Magnets attract magnetic materials

The magnetic force exerted by a magnet can attract magnetic materials. The difference between magnetic and non-magnetic materials is the ability to be attracted by a magnet.

Magnetic materials are materials that can be attracted to a magnet.

Non-magnetic materials are materials that cannot be attracted to a magnet.

Table 15.1 lists some examples of magnetic and non-magnetic materials.

Table 15.1 *Examples of magnetic and non-magnetic materials*

Magnetic materials	Non-magnetic materials
Steel	Copper
Iron	Wood
Cobalt	Plastic
Nickel	Brass

This property of magnet is useful when we are separating magnetic materials from non-magnetic materials in a metal scrapyard.

The poles of magnets have the strongest magnetic force

The ends of a magnet are also known as poles. When we move a magnet close to a pile of iron nails, the iron nails are attracted to the poles of the magnet (Figure 15.2). The poles are where the magnetic force is the strongest.

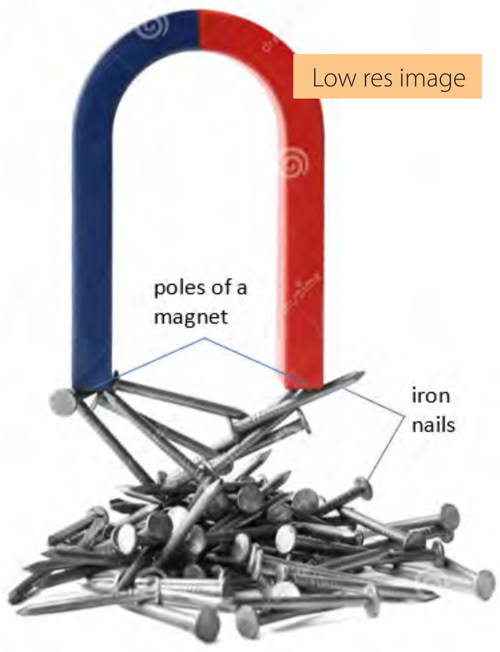


Figure 15.2 The iron nails are attracted to the poles of the magnet.

A freely suspended magnet points to the north–south direction

When a magnet is left suspended freely, it always points to the North and South Poles of the Earth (Figure 15.3).

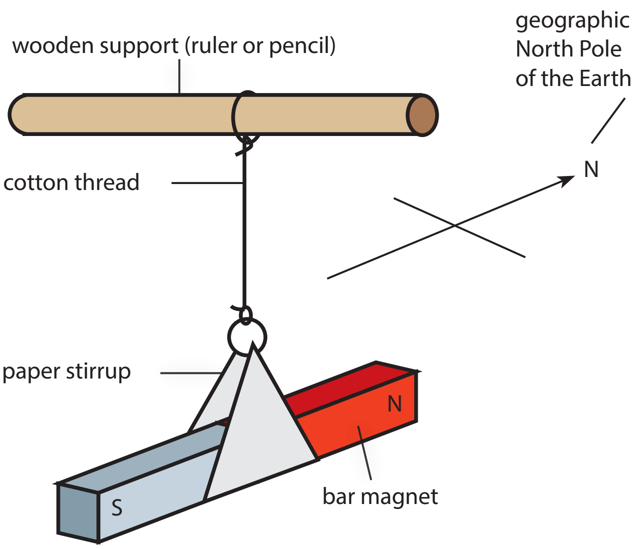


Figure 15.3 A bar magnet always points to the north–south direction when suspended freely.

This is because the Earth behaves like a giant magnet and the magnetic force exerted by the Earth causes a freely suspended magnet to point in the north-south direction of the Earth. The poles of magnets are also known as north pole (N pole) and south pole (S pole) due to this property.

LINK

Find out how the Earth affects the direction of a freely suspended magnet in Section 15.3 of this chapter.

ENRICHMENT ACTIVITY

Design your own levitating toy using the properties of magnets. What property allows the toy to **levitate**?

Share your findings with the class.

QUICK CHECK

The N pole of a magnet will attract the S pole of another magnet.

True or false?

WORD ALERT

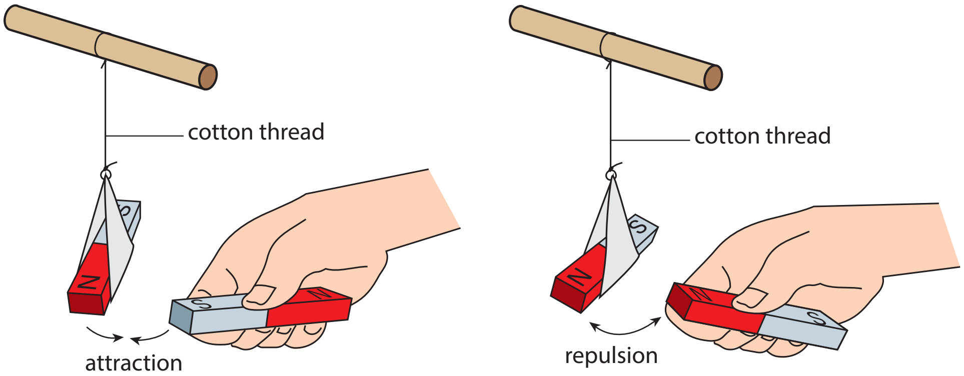
Levitate: float

Magnetising: making something to have the properties of a magnet

Induced: made to become, caused to happen

Like poles repel, unlike poles attract

When we bring two like poles (two north poles or two south poles) of two magnets together, the magnetic force between the poles of the magnets causes them to **repel** each other. When we repeat this with two unlike poles, the two magnets **attract** each other (Figure 15.4).



Unlike poles attract. Like poles repel.

Figure 15.4 *Attracting and repelling magnets*

What is induced magnetism?

Magnets are made by **magnetising** magnetic materials. The process of magnetising a magnetic material is also known as **magnetic induction**.

When an unmagnetised paper clip is brought near a bar magnet, it is attracted to the magnet. When this happens, we say the paper clip has become an **induced magnet**. In turn, this **induced** magnet is able to attract other paper clips (Figure 15.5).

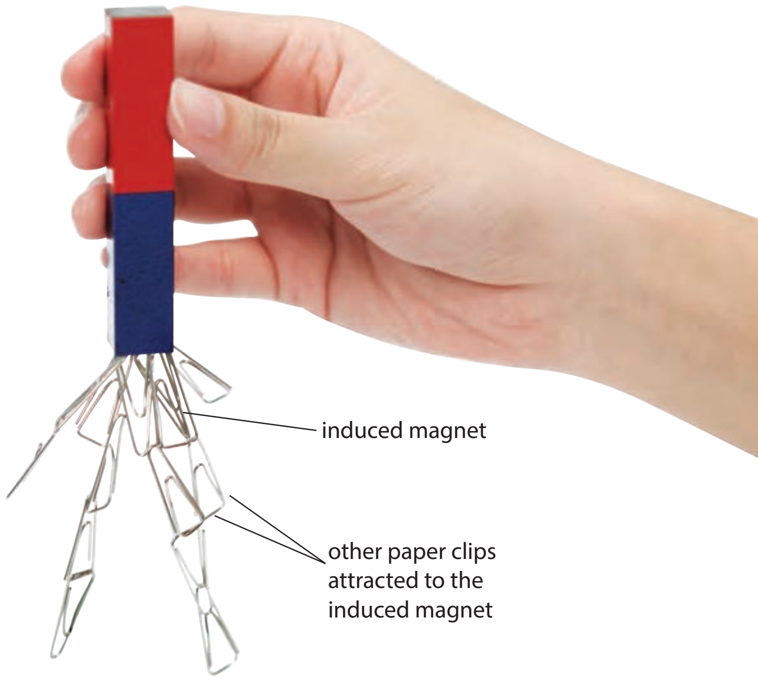


Figure 15.5 *Paper clips attracted by a magnet become induced magnets that attract other paper clips.*

The process of induction does not require physical contact. As shown in Figure 15.6, the magnet can induce magnetism in the iron bar by simply being near it. The N pole of the bar magnet induces an S pole in the nearer end of the iron bar and an N pole in its farther end.

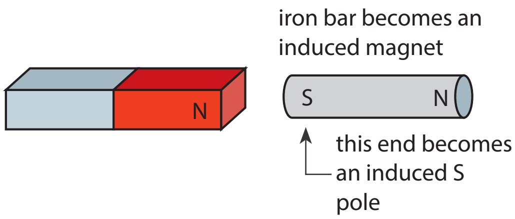


Figure 15.6 *A magnetic material is induced when a magnet is placed close to it.*

Magnetic materials can be magnetised because of the presence of *magnetic domains*. Each domain behaves like a small magnet, and we can represent them using arrows (Figure 15.7). The arrowhead shows the N pole and the back of the arrow shows the S pole.

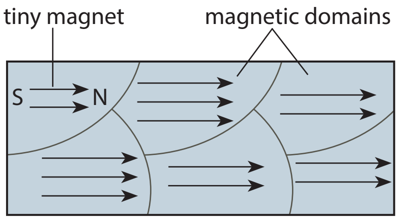
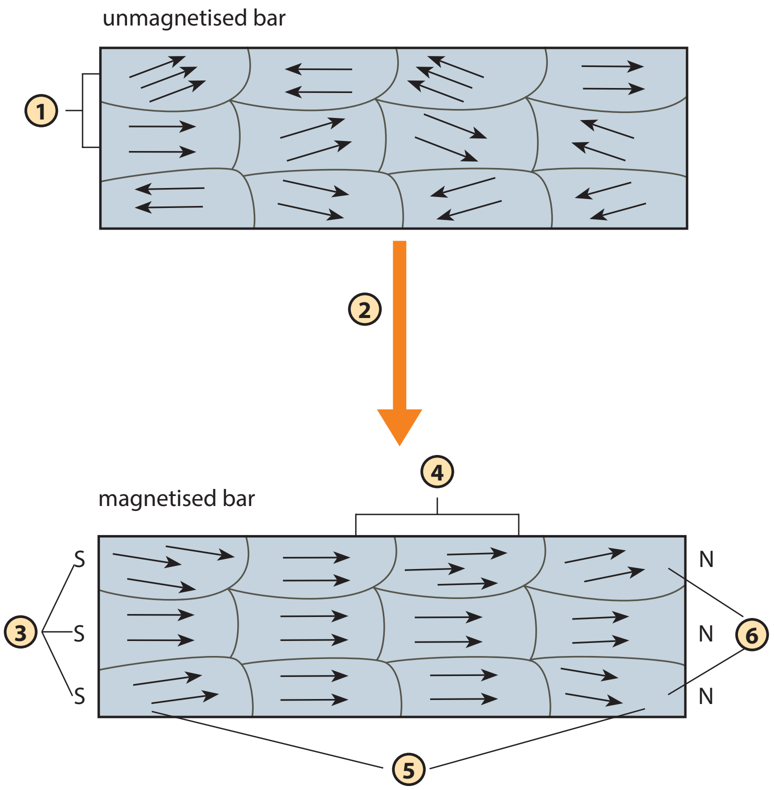


Figure 15.7 *Magnetic domains in a magnetic material*

Figure 15.8 explains how a magnetic material is magnetised.



1. The magnetic domains in an unmagnetised bar point in random directions. There is no net magnetisation because the domains cancel one another out.
2. The N pole of a magnet is placed on the left side of the unmagnetised bar.
3. The magnetic force from the magnet causes the S poles of the domains, nearest to the magnet, to be attracted to the magnet. All other domains rotate and point in the same direction, producing a net magnetisation.
4. Each arrow is arranged directly behind the arrow in front of it. Therefore, the N poles are cancelled out by the adjacent S poles.
5. The tiny magnets at both the ends are 'free'. This produces the effect of N or S poles at the ends. This allows the magnetised bar to behave like a magnet.
6. The tiny magnets at the ends tend to fan out due to repulsion between the like poles.

Figure 15.8 *The alignment of the domains causes a magnetic bar to be magnetised.*

ENRICHMENT INFO

Magnetic Resonance Imaging (MRI)

An MRI machine can take images of a patient's body by using very strong magnets. This is because we have many protons in our body, which act like tiny magnets. The movement of these tiny magnets caused by the strong magnets in the MRI machine can be studied to find out more about what is happening in our body.

An MRI image of the blood vessels in the brain

QUICK CHECK

An S pole of a magnet was brought close to an iron bar. The iron bar was repelled by the magnet. The N pole of the same magnet was brought close to the iron bar. The iron bar was attracted to the magnet.

True or false?

PHYSICS WATCH

Scan this page to explore a simulation on magnetic induction.

Let's Practise 15.1

1 Give three examples of
  (a) magnetic materials;
  (b) non-magnetic materials.

2 State the properties of magnets.

3 In an experiment, a piece of wood is held between the N pole of a magnet and two iron nails (Figure 15.9).
  (a) Although wood is a non-magnetic material, the two nails are still attracted to the magnet when the piece of wood is held between the magnet and the nails. Suggest a reason for this.
  (b) It is observed that the pointed tips of the iron nails point away from each other. Why?

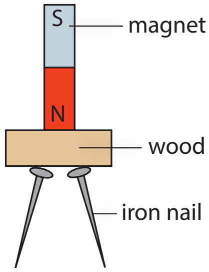


Figure 15.9

4 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

Exercise 15A, pp. XX–XX

15.2 Temporary and Permanent Magnets

In this section, you will learn the following:
- State the differences between the properties of temporary and permanent magnets.
- Describe the uses of permanent magnets and electromagnets.

What are temporary and permanent magnets?

Both iron and steel are magnetic materials. Magnets made from iron are known as temporary magnets, while magnets made from steel are known as permanent magnets. This is because iron and steel have different magnetic properties.

Most types of iron are **magnetically soft**. A magnetically soft material can be easily magnetised and also lose its magnetism easily. Iron that is magnetically soft is also known as soft iron. Steel is **magnetically hard**. A magnetically hard material is difficult to magnetise, but once magnetised, retains its magnetism afterwards. The properties of soft iron and steel can be observed in Let's Investigate 15A.

WORD ALERT A-Z

Temporary: lasting for a short time

Permanent: lasting for a long time

ENRICHMENT *THINK*

What are some instances where a temporary magnet is preferred over a permanent magnet? How about the other way around?

Let's Investigate 15A

Objective

To compare the magnetic properties of soft iron and steel

Materials

Bar magnet, soft iron and steel bars of equal dimensions (20 cm in length), iron paper clips

Procedure

1 Let the N pole of the bar magnet attract one end of the soft iron bar. Dip the other end of the soft iron bar into a tray of paper clips. Record the maximum number of paper clips that are attracted to it.

2 Pull the magnet away from the soft iron bar. Observe what happens to the paper clips. Record the number of paper clips still attracted to the soft iron bar.

3 Now repeat steps 1 and 2 using the steel bar.

4 Repeat steps 1–3 and observe whether there are consistent differences in the observations between the two metal bars.

Observation and results

Figure 15.10 summarises what happens when we conduct the investigation.

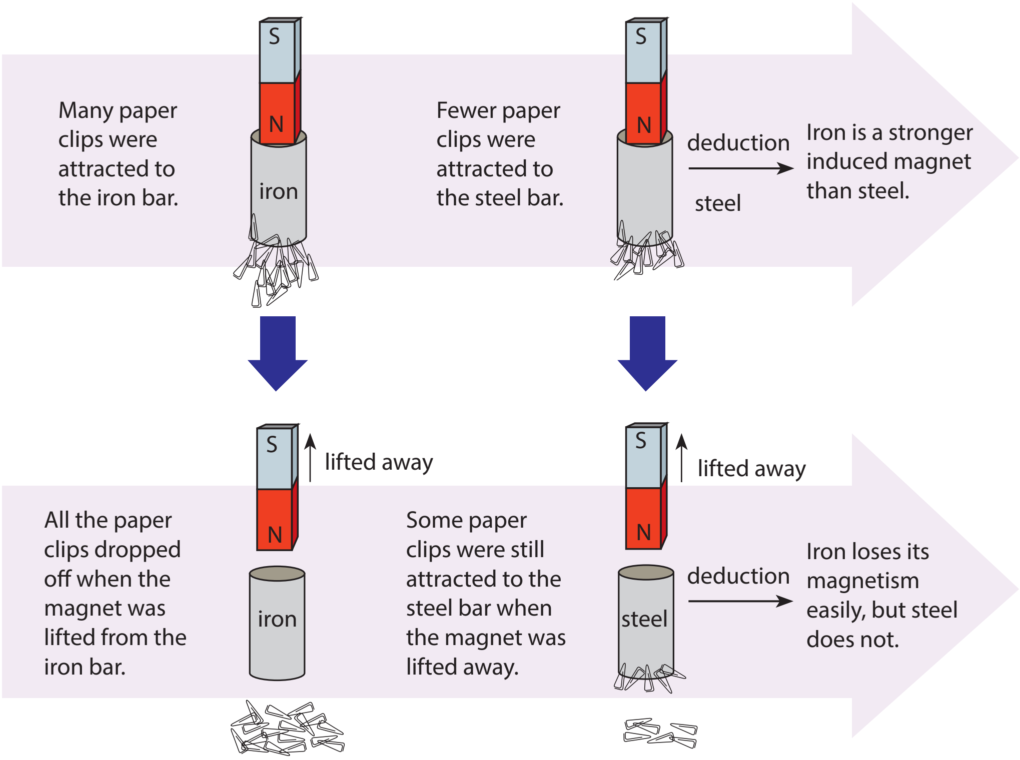


Figure 15.10

Conclusion

The different magnetic properties of soft iron and steel are summarised in the table below.

Table 15.2 *Magnetic properties of soft iron and steel*

Magnetic properties of soft iron	Magnetic properties of steel
• It is easily magnetised to become a stronger induced magnet.	• It is difficult to magnetise. Hence, it becomes a weaker induced magnet.
• It loses its magnetism easily.	• It does not lose its magnetism easily.

PHYSICS WATCH

Scan this page to explore a simulation on temporary and permanent magnets.

PWB LINK

Practical 15A, pp. XX–XX

LINK

An electromagnet is a type of temporary magnet. Placing a magnetically soft material within an electromagnet produces a stronger temporary magnet. You will learn more about this in Chapter 17.

What can we do with permanent magnets and electromagnets?

Magnets are used in many parts of our lives. Permanent magnets are used when a constant magnetic force is needed. Electromagnets are used when a changing magnetic force is needed. Figure 15.12 shows how magnets are used in our daily lives.

Figure 15.12 *Uses of magnets*

Uses of permanent magnets

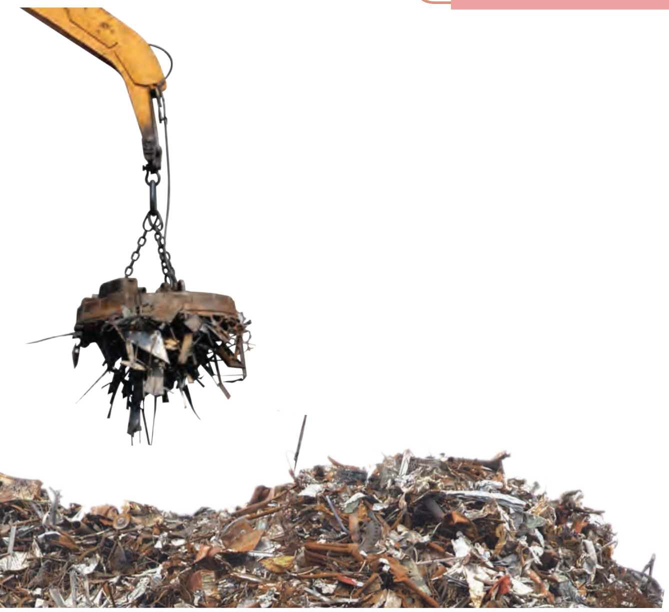
Magnetic door catches

Magnetic strips made of permanent magnets are fitted to the door of a refrigerator. When the door is closed, the attraction between the magnetic strip and the steel frame keeps the door closed.

Maglev trains

Magnetic levitation (maglev) trains use magnetic attraction and repulsion to levitate and move forward. As the trains are not in contact with the tracks, friction is reduced and the trains can move at high speeds.

Uses of temporary magnets



Electromagnets

Electromagnets are magnets that form when a current flows through a coil. This magnetic field can induce magnetism in a soft magnetic material to produce a temporary magnet.

Cranes use electromagnets to separate magnetic materials from non-magnetic materials in metal scrapyards.

Let's Practise 15.2

1 Figure 15.13 shows an experiment in which identical magnets are clamped to the ends of three metal bars. Each metal bar is made of a different metal — brass, iron and steel. The number of iron tacks picked up by each metal bar is shown. Identify metals 1, 2 and 3, and explain your answer.

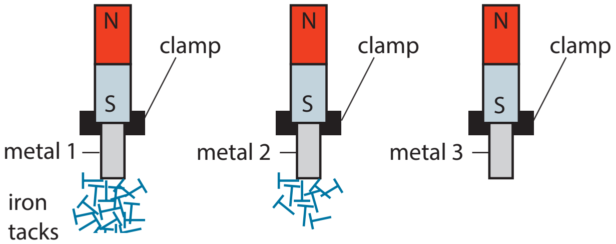


Figure 15.13

2 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

TWB LINK
Exercise 15B, pp. XX–XX

15.3 Magnetic Field

In this section, you will learn the following:

- Describe a *magnetic field* as a region in which a magnetic pole experiences a force.
- Draw the pattern and direction of magnetic field lines around a bar magnet.
- Describe the plotting of magnetic field lines with a compass and the use of a compass to determine the direction of the magnetic field.
- State that the direction of a magnetic field at a point is the direction of the force on the N pole of a magnet at that point.
- S Explain that magnetic forces are due to interactions between magnetic fields.
- S Know that the relative strength of a magnetic field is represented by the spacing of the magnetic field lines.

What is a magnetic field?

Every magnet has a region of space around it called a **magnetic field**. Earth behaves like a giant magnet and has its own magnetic field (Figure 15.14).

A magnetic material or magnetic pole placed in the magnetic field will experience a force. We have learnt in Section 15.1 that a freely suspended magnet points in the north–south direction. As the freely suspended magnet is placed in the magnetic field of Earth, the magnet experiences a magnetic force from Earth.

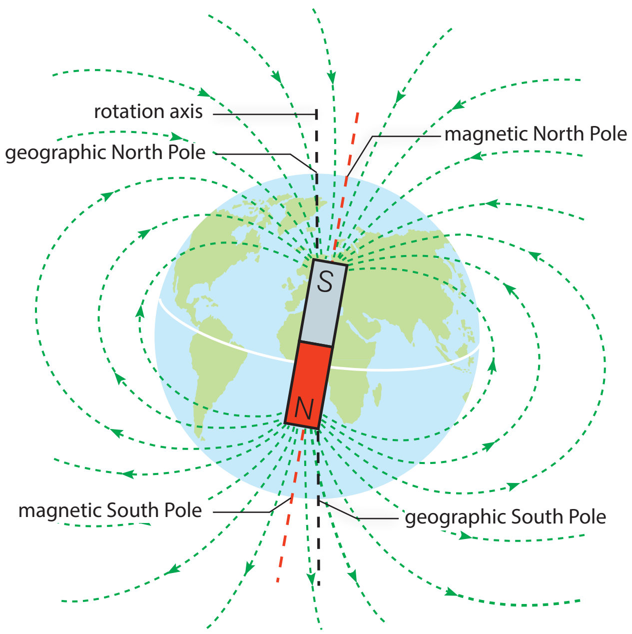


Figure 15.14 *Earth's magnetic field*

HELPFUL NOTES

We can use a compass to determine the direction of the magnetic field easily. The arrowhead of the compass shows the direction of the magnetic field at that point.

QUICK CHECK

A piece of wood placed in the magnetic field of a magnet experiences magnetic force.

True or false?

The arrangement of a group of magnetic field lines is called a **magnetic field pattern**.
The magnetic field pattern of a magnet shows us the magnetic force acting on a magnetic material or magnet placed in the field:

- The *direction* of the magnetic field lines at a point is the direction of the force on the N pole of a magnet at that point.
- S The *relative strength* of the magnetic force is dependent on how closely packed the magnetic field lines are.

How can we visualise the magnetic field of a magnet?

A magnetic field is invisible. To visualise the pattern and direction of the magnetic field around a bar magnet, we can use a **plotting compass**, which is a small magnet. When a plotting compass is placed near a bar magnet, their opposite poles will attract each other. The procedure is described in Let's Investigate 15B.

Let's Investigate 15B

Objective
To determine the shape and direction of the magnetic field lines around a bar magnet

Materials
Bar magnet, plotting compass, plain paper, pencil

Precautions

- Perform this experiment away from other magnetic materials such as steel, iron and nearby electrical cables.
- Check that the compass needle is free to rotate about the pivot at its centre.

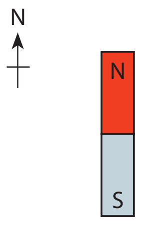


Figure 15.15

Procedure

1. Put the bar magnet at the centre of a piece of paper. Ensure that its N pole points to the north (Figure 15.15). Use a compass to help you determine the north direction.
2. Trace the outline of the magnet, and indicate its N pole and S pole.
3. Starting near one pole of the magnet, mark the positions of the ends, S and N, of the compass needle with pencil dots X and Y respectively. Move the compass so that the S end is at Y and mark the new position of the N end with a third dot Z (Figure 15.16).
4. Repeat the process of marking the dots until you reach the other pole. Join the dots and this will give a single magnetic field line.
5. Determine the direction of the field line by checking the arrow of the compass needle. The compass needle should point to the S pole of the magnet as shown in Figure 15.15.
6. Repeat steps 3 to 5, starting at different points near the N pole until several field lines have been drawn. Try to keep the field lines symmetrical by going above and below the magnet on the piece of paper.

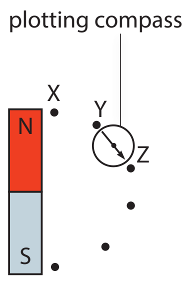


Figure 15.16

Observations and conclusion

- The magnetic field lines appear to leave the North pole and end at the South pole of the magnet, with a pattern similar to that in Figure 15.17.
- The direction of the magnetic field lines can be determined using a compass.
- S The field lines are more concentrated at the poles. This is because the field lines are closest together on the diagram at the poles. We learnt that the magnetic force is the strongest at the poles. Hence, we can conclude that the closer the magnetic field lines, the stronger the magnet.

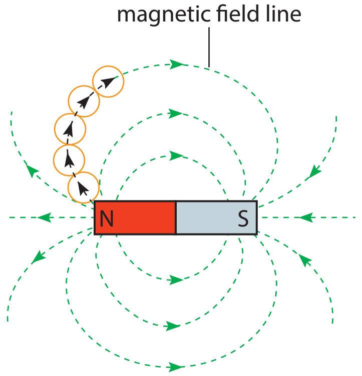


Figure 15.17 *Field lines around a bar magnet*

LINK PWB
Practical 15B, pp. XX–XX

S We learnt that every magnet has a magnetic field. The plotting compass is a tiny magnet. *The interaction of the magnetic fields of the bar magnet and the plotting compass results in a magnetic force*. This magnetic force exerted by the bar magnet on the plotting compass needle rotates the needle to point along one of the bar magnet's field lines. This explains why we can use a plotting compass to plot the magnetic field lines around a magnet.

Let's Practise 15.3

1 Figure 15.18 shows a plotting compass placed at a position near a bar magnet.

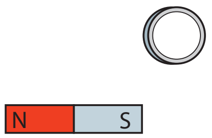


Figure 15.18

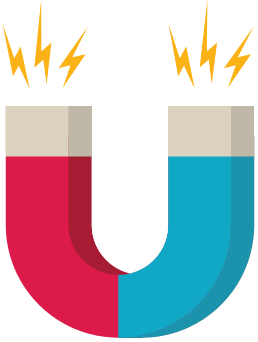
(a) Draw the magnetic field lines around the bar magnet.
(b) Determine the direction of the arrow in the plotting compass at that position.
(c) The bar magnet is then replaced with a stronger bar magnet. Draw the magnetic field lines around the stronger bar magnet.

2 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB
Exercise 15C–15D, pp. XX–XX
Exercise 15E Let's Reflect, p. XX

Let's Map It

MAGNETISM



Magnet

have the following properties

- Attract magnetic materials
- Have a north pole and a south pole, with the strongest magnetic force
- When suspended freely, rest in north-south direction
- Obey the laws of magnetism (like poles repel, unlike poles attract)

due to

Magnetic force

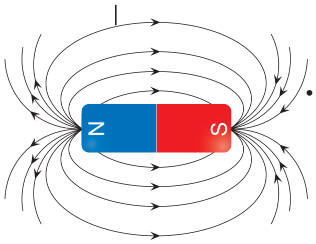
caused by

Ⓢ Interactions between magnetic fields

which is

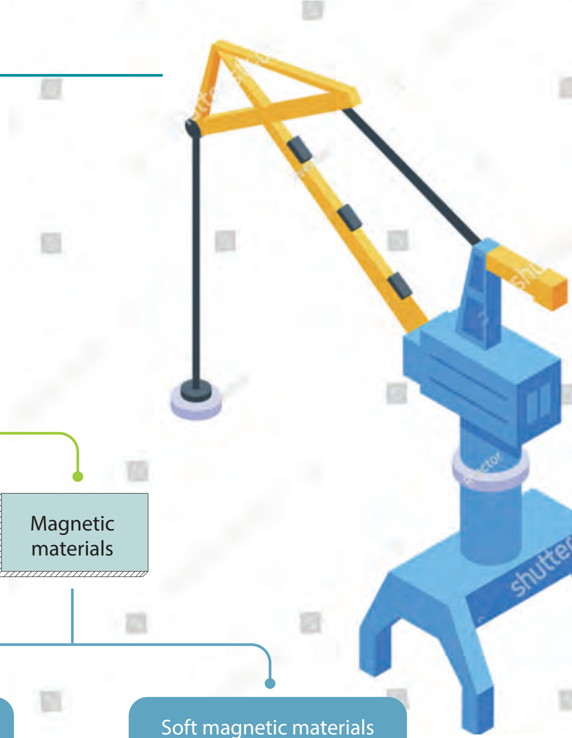
Visualised using plotting compass

magnetic field line



where

- The direction of the magnetic field lines at a point is the direction of the force on the N pole of a magnet at that point.
- Ⓢ The relative strength of the magnetic force is dependent on how closely packed the magnetic field lines are.



Magnetic materials

Hard magnetic materials

which are difficult to magnetise through

Soft magnetic materials

which are easy to magnetise through

Induced magnetism

to form

Permanent magnets

used in

Magnetic door catches

Maglev trains

Temporary magnets

used in

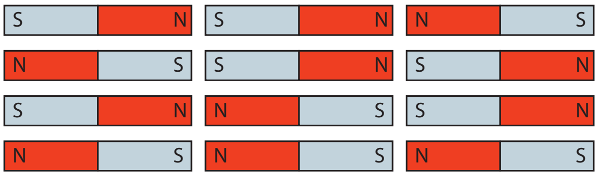
Maglev trains

Electromagnets

Let's Review

Section A: Multiple-choice Questions

1 In which of the following set-ups will all three magnets repel one another?



2 Figure 15.19 shows a small compass placed near the centre of a bar magnet.

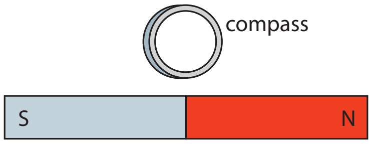
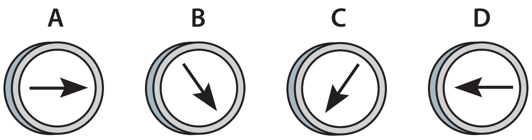


Figure 15.19

In which direction will the compass needle point?



3 Figure 15.20 shows part of a magnetic relay. M is the magnet located inside the coil. L is the armature that is attracted to M when a current flows through the coil. S is the stopper that cushions the impact of L on M during attraction. It prevents L and M from being damaged during collision.

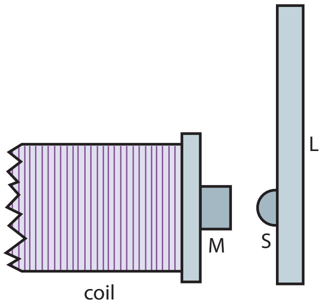


Figure 15.20

Which of the following gives the best combination of materials for M, L and S?

	M	L	S
A	Iron	Copper	Rubber
B	Iron	Iron	Iron
C	Iron	Iron	Rubber
D	Plastic	Iron	Rubber

Section B: Short-answer and Structured Questions

1 Steel is known as a magnetically hard material. It can be made into a permanent magnet through induced magnetism.

(a) State what is meant by the term "magnetically hard"?

(b) Explain how magnetism is induced in a steel.

(c) Other than steel, name a magnetic material that is magnetically soft.

2 Describe an experiment to determine the shape and direction of the magnetic field lines around a bar magnet.

3 S Explain what causes magnetic forces

(a) between magnets;

(b) between magnets and magnetic materials.

4 Figure 15.21 shows a rod of unmagnetised steel placed inside a solenoid. When the switch is closed, current flows through the solenoid and the steel rod is magnetised.

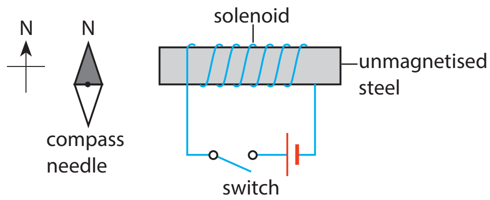


Figure 15.21

(a) Describe the motion of the compass needle when the switch is closed and then opened some time later.

(b) Describe how the experimental set-up in Figure 15.21 can be used to distinguish a steel rod from an iron rod. List any additional materials that will be used.

5 Figure 15.22 shows a soft iron bar placed near a bar magnet.

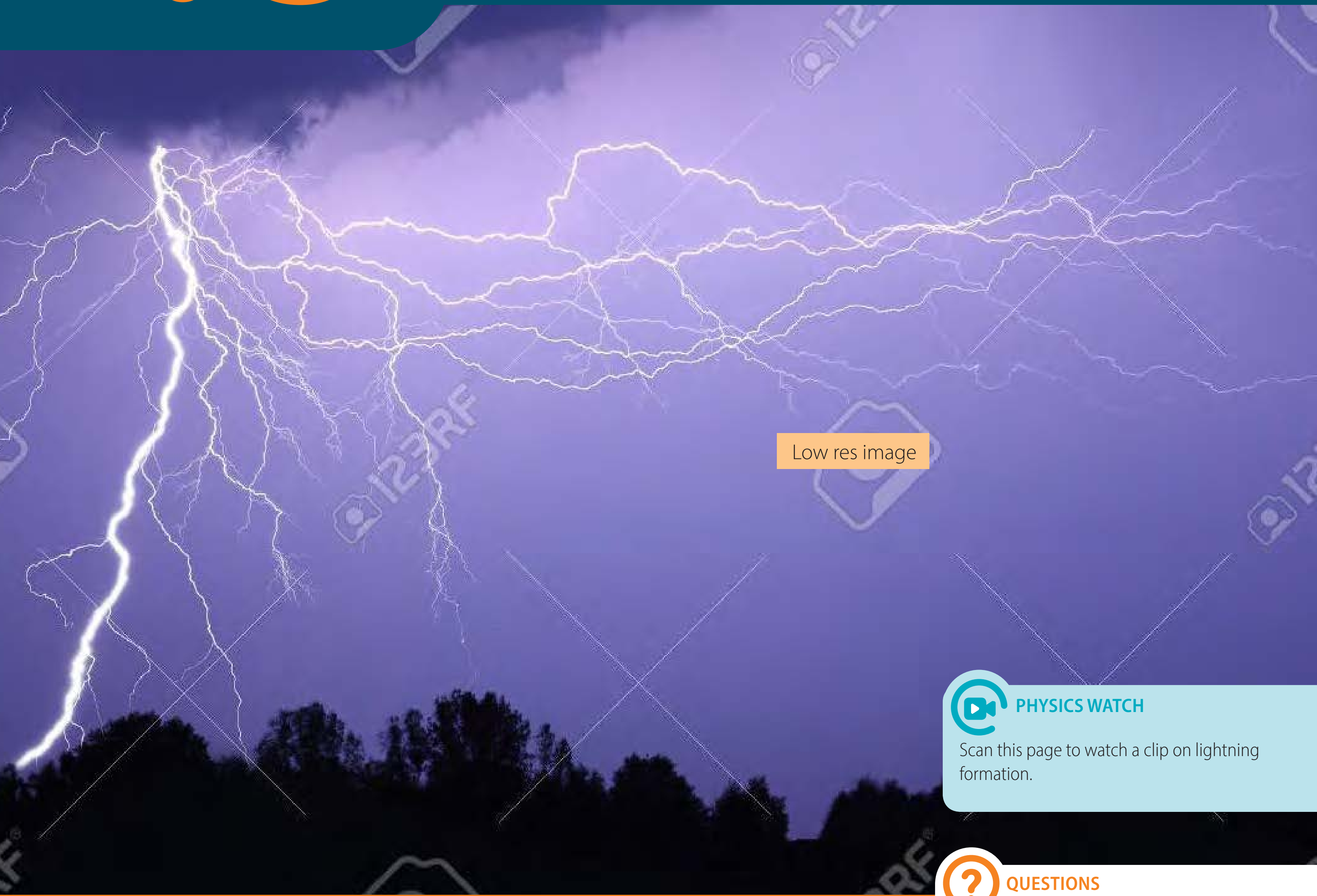
Figure 15.22

(a) Draw the magnetic field pattern of the soft iron bar shown in Figure 15.22. Indicate the poles of the induced magnet and the direction of the field lines.

(b) Using a diagram, outline how you can check your answer in (a) with an experiment using a plotting compass.

CHAPTER

16 Electrical Quantities



PHYSICS WATCH

Scan this page to watch a clip on lightning formation.

QUESTIONS

- What do you think causes lightning?
- Why do you think lightning strikes frequently in the Himalayas?
- What precautions should you take to avoid being hit by lightning during a thunderstorm?

Lightning is a spectacular sight, but be sure to observe it from a safe place. According to statistics, Asia has the second-most number of lightning hotspots. Very high rates of lightning activity can be found along the high regions of the Himalayas.

Daggar is a small town about 100 km from Islamabad, the capital of Pakistan. It lies near the north-western ridges of the Himalayas. Daggar recorded 143 lightning hits per year, making it the top lightning hotspot in Asia.

16.1 Electric Charge

In this section, you will learn the following:

- State that there are positive and negative charges.
- State that positive charges repel other positive charges, negative charges repel other negative charges, but positive charges attract negative charges.
- Describe simple experiments to show the production of electrostatic charges by friction and to show the detection of electrostatic charges.
- Explain the charging of solids by friction involves only a transfer of negative charge (electrons).
- Describe an experiment to distinguish between electrical conductors and insulators.
- Recall and use a simple electron model to explain the difference between electrical conductors and insulators and give typical examples.

When you rub a balloon against your hair, the balloon attracts your hair (Figure 16.1). Why?

Both the balloon and your hair acquire a static electric charge due to the friction from rubbing. These charges cause the attraction between the balloon and your hair. How do objects become charged by rubbing?

WORD ALERT

Static: not moving

Figure 16.1 Rubbing a balloon against your hair charges both the balloon and your hair.

Simple electron model

To understand how objects become charged by rubbing, we must first understand that all objects are made up of tiny particles called atoms. Let's use a simple electron model to understand what makes up an atom.

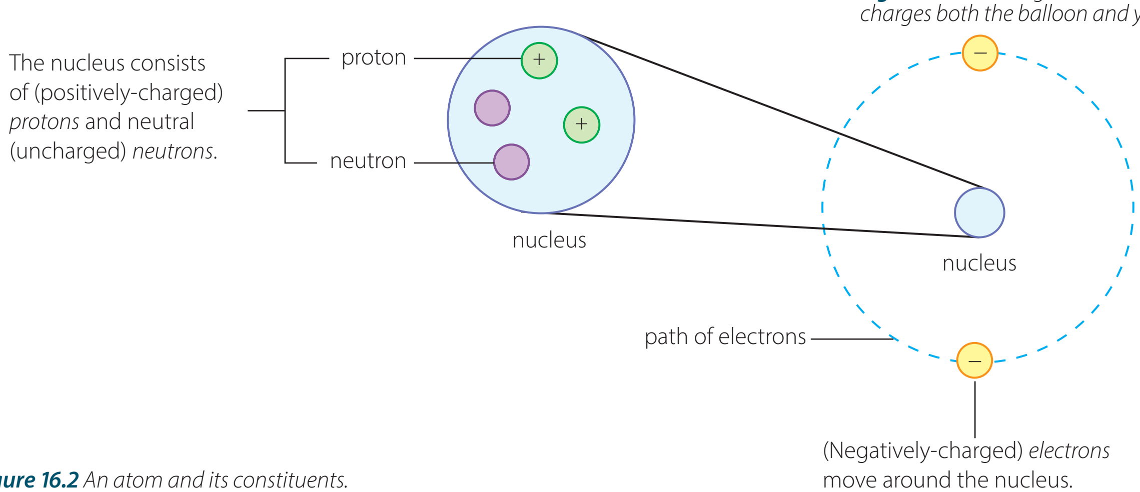


Figure 16.2 An atom and its constituents.

In an atom, there is a central **nucleus**. The nucleus is made up of **protons** and **neutrons**. Around the nucleus are the orbiting **electrons**. There are positive and negative charges in the atom. Protons are the positive charges while electrons are the negative charges.

An atom has an equal number of electrons and protons — it is electrically neutral. An atom becomes charged when the number of electrons and protons is not equal. This occurs when electrons are removed from or added to the atom. If electrons are removed, the atom becomes positively charged. If electrons are added, the atom becomes negatively charged. Let us now look at Let's Investigate 16A to find out how a glass rod can be charged by the movement of electrons.

Let's Investigate 16A

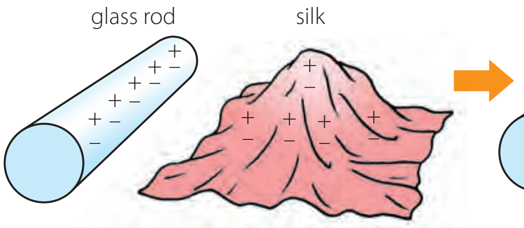
Objective
To show how a glass rod can be charged by friction

Materials
Rubber mat, two glass rods, silk, a few pieces of paper

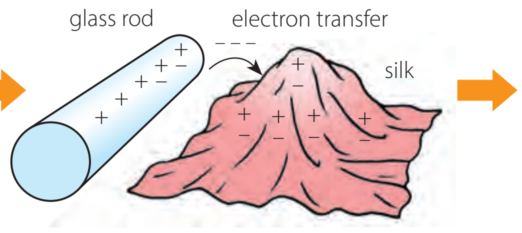
Procedure
1 Stand on a rubber mat and hold a glass rod
2 Rub the glass rod with a piece of silk for three minutes. Label this rod A
3 Bring the glass rod close to a few pieces of paper.
4 Observe what happens to the pieces of paper.
5 Label the second glass rod B.
6 Bring the rod B to the pieces of paper. Observe what happens.

Observation
The pieces of paper are attracted to rod A but not rod B.

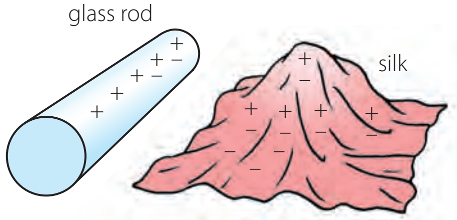
Discussion



Before rubbing, the glass rod and the piece of silk are electrically neutral, i.e. they each contain an equal number of protons and electrons.



- Different materials have different **affinities** for electrons, i.e. some materials attract electrons weakly, whereas others attract electrons strongly.
- When the glass rod and the piece of silk are rubbed together, the atoms at their surfaces are disturbed.
- Some electrons from the atoms at the surface of the glass rod are transferred to the piece of silk.



As the glass rod loses electrons, it becomes positively charged. As the piece of silk gains electrons, it becomes negatively charged.

Figure 16.3 *Charging by friction*

WORD ALERT

Affinities: natural attraction

LINK PWB

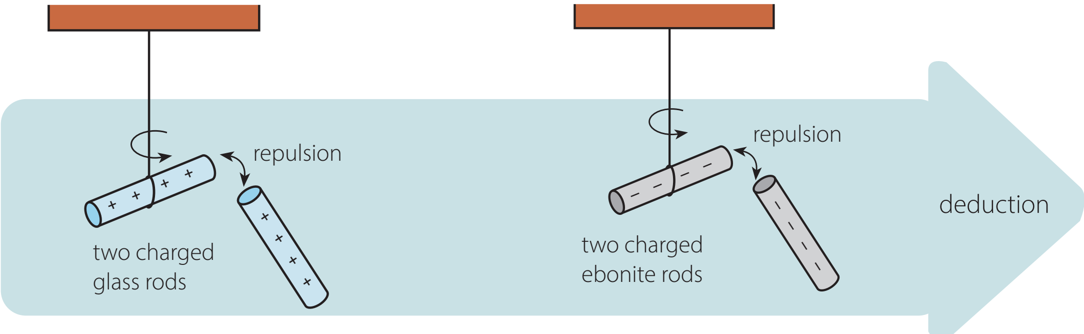
Practical 16A, pp. XX–XX

Conclusion

A material can become charged when rubbed with another material. This is because *rubbing transfers electrons* from one material to the other material.

Interactions between charges

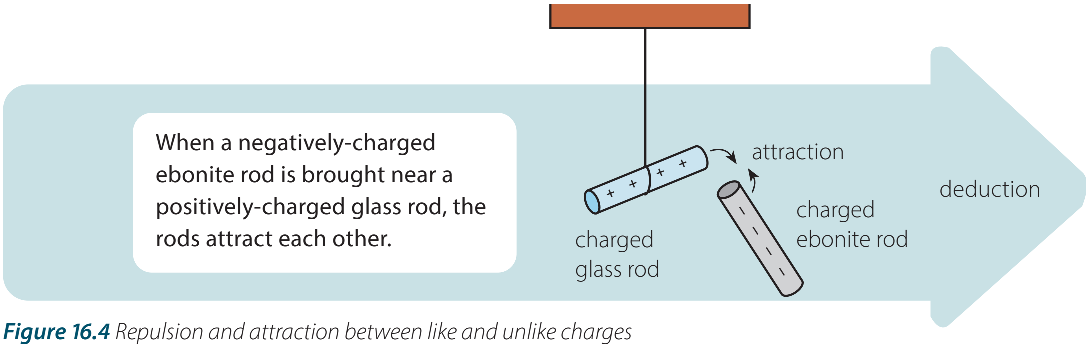
Positive charges repel other positive charges. Negative charges repel other negative charges. Positive charges attract negative charges.



Like charges repel.

When two positively-charged glass rods are brought near each other, the glass rods repel each other.

When two negatively-charged ebonite rods are brought near each other, the ebonite rods repel each other.



Unlike charges attract.

Figure 16.4 *Repulsion and attraction between like and unlike charges*

The glass rod and the ebonite rod are examples of electrical insulators. Electrical insulators are materials in which electrons are not free to move about. Electrical insulators can be charged by friction as they gain or lose electrons when they are rubbed together.

Materials in which electrons are free to move about are electrical conductors. All metals are conductors. Let us check if a material is a conductor or an insulator using Let's Investigate 16B.

PHYSICS WATCH

Scan this page to explore a simulation on how friction can cause an electric shock.

Let's Investigate 16B

Objective

To check which materials are conductors and which are insulators

Materials

1.5V dry cell, crocodile clips with connecting wires, switch, copper rod, aluminium rod, glass rod, wooden rod (ideally the same dimensions for all the rods), 1.5V rated lamp

Precautions

Make sure that you perform this experiment with a low voltage and never use the circuit without the lamp. If it is omitted, the wires can heat up very quickly and has the capacity to cause a burn.

WORD ALERT

Omitted: left out, excluded

Procedure

1 Connect the dry cell, crocodile clips with connecting wires, the lamp and the switch as shown in Figure 16.5.
2 Close the switch. If the circuit has been built correctly and the components are functioning, the lamp should light up.
3 Connect the copper rod between the dry cell and the switch as shown in Figure 16.6.
4 Close the switch.
5 Observe whether the lamp lights up.
6 Repeat steps 3 to 5 with the other rods.

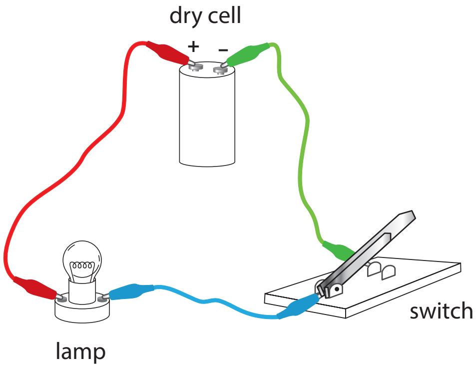


Figure 16.5

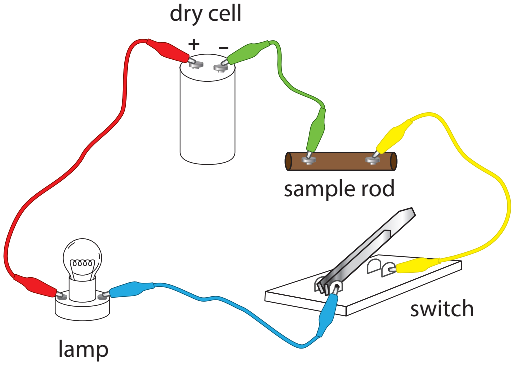


Figure 16.6

Observation

The lamp lit up when the copper rod and the aluminium rod were connected. The lamp did not light up when the glass rod and the wooden rod were connected.

Conclusion

For some materials, when the switch was closed, the lamp lit. These materials are called *electrical conductors*. Examples of electrical conductors are copper, aluminium and silver. For some materials, when the switch was closed, the lamp did not light. These materials are called *electrical insulators*. Examples of electrical insulators are plastics, wood and glass.

LINK PWB
Practical 16A, pp. XX–XX

Let's Practise 16.1

1 State the two types of electric charges.
2 Two polythene rods are each rubbed with wool. When the two rods are suspended and brought close to each other.
   (a) Describe what is observed.
   (b) Explain what is observed.
3 Explain the difference between an electrical insulator and an electrical conductor.
4 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB
Exercise 16A, pp. XX–XX

S

16.2 Electric Field

In this section, you will learn the following:

- S Describe an electric field as a region in which an electric charge experiences a force.
- S State that the direction of an electric field at a point is the direction of the force on a positive charge at that point.
- S Describe simple electric field patterns, including the direction of the field around a point charge, a charged conducting sphere and between two oppositely charged parallel conducting plates.

Just like the magnetic field that is around a magnet, there is an electric field around every charge, represented by lines and arrows. An electric field is a region in which an electric charge experiences a force (Figure 16.7).

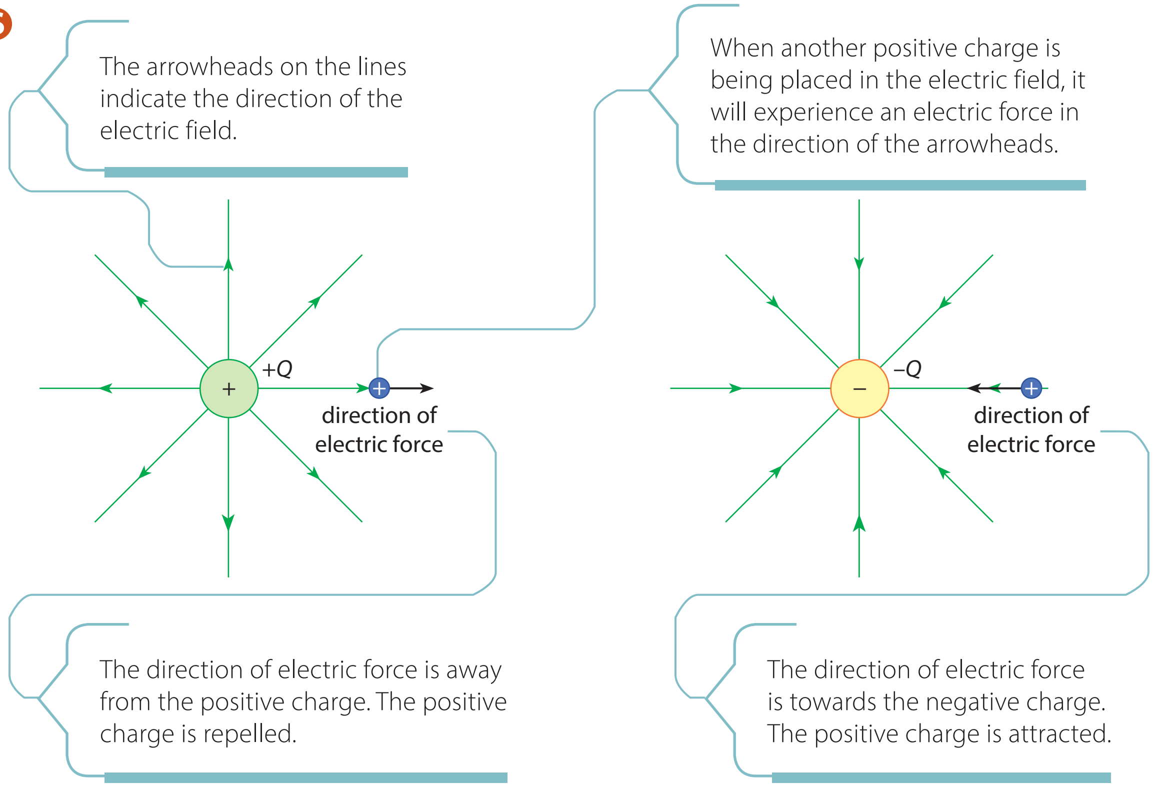


Figure 16.7 *Direction of electric force on a test charge in an electric field*

Therefore, the direction of an electric field at a point is the direction of the force on a positive charge at that point.

Figure 16.8 shows the simple electric field pattern around different charged objects.

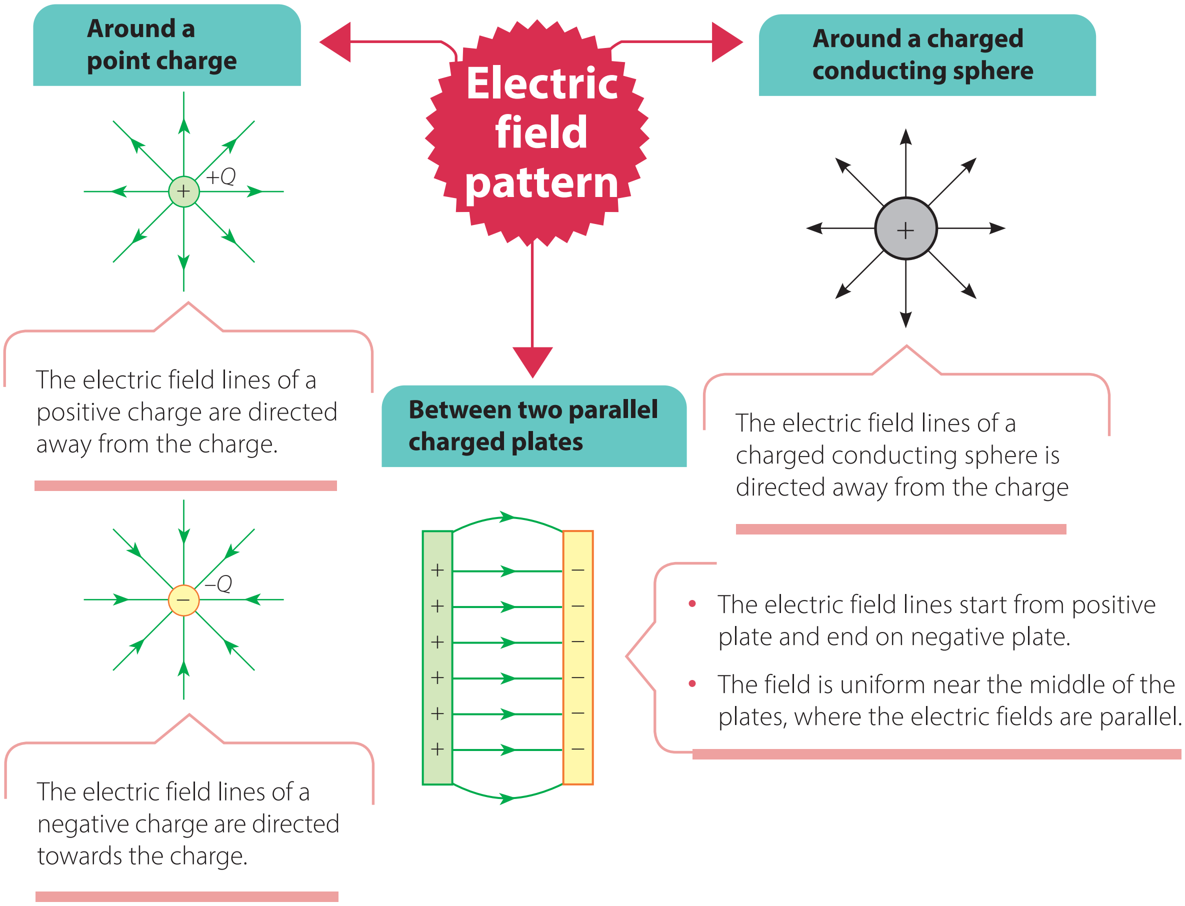


Figure 16.8 *Simple electric field pattern around different charged objects.*

LINK

Recall from Chapter 15 that

- the direction of the field lines shows the direction of a force; and
- the strength of the field is dependent on how closely packed the filled lines are.

HELPFUL NOTES

The field lines around the conducting sphere are very much the same as that for a point charge.

Consider a sphere of radius R that the has a charge of Q on it. The electric field line pattern outside the sphere is exactly the same as a point charge Q at the centre of that sphere.

ENRICHMENT ***THINK***

There are no electrical field lines inside a sphere of charge Q. Explain why.

LINK TWB

Exercise 16B, pp. XX–XX

Let's Practise 16.2

1. **S** Compare the direction of an electric field at a point and the direction of the force on a positive charge at that point.
2. **S** Sketch the electric field lines due to an isolated negative charge.
3. **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

16.3 Electric Current

In this section, you will learn the following:

- Know that electric current is related to the flow of charge.
- **S** State that charge is measured in coulombs.
- **S** Define *electric current*; recall and use the equation $I = \frac{Q}{t}$.
- **S** State that conventional current is from positive to negative and that the flow of free electrons is from negative to positive.
- Describe electrical conduction in metals in terms of the movement of free electrons.
- Describe the use of ammeters, analogue and digital, with different ranges.
- Know the difference between direct current (d.c.) and alternating current (a.c.).

What is electric current?

An object becomes charged if electrons are added to or removed from it. When the charged object is provided with a conducting path, electrons start to flow through the path from or to the object.

When electrons move, we say that an electric current is produced. An electric current is formed by moving electrons. Therefore, electric current is related to the flow of charge.

HELPFUL NOTES

Throughout this book, we will refer to conventional current unless otherwise stated.

S

An electric charge, Q, is measured in **coulombs (C)**. The amount of charge carried by an electron or proton is 1.6×10^{-19} C.

Electric current is the charge passing a point per unit time. The SI unit of electric current is the **ampere (A)**.

In symbols, electric current is given by:

$\boldsymbol{I = \frac{Q}{t}}$ where I = current (in A);

Q = charge (in C);

t = time taken (in s).

What is conventional current?

Before the discovery of electrons, scientists believed that an electric current consisted of moving positive charges. Although this belief was later proven wrong, the idea is still widely held. This is because the discovery of electron flow did not affect the basic understanding of an electric current, which is the movement of charges. This 'movement' of positive charges is called *conventional current*.

Conventional current is from positive to negative and that the flow of free electrons is from negative to positive.

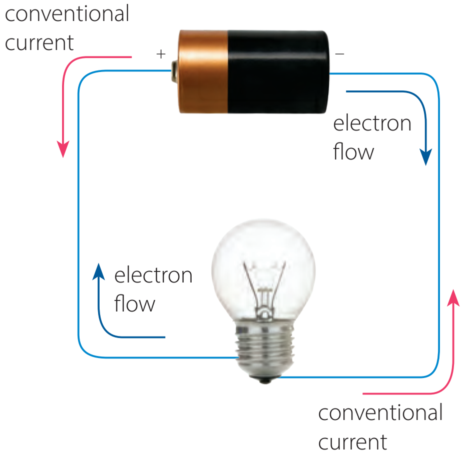


Figure 16.9 *Conventional current versus electron flow*

An electric current is actually caused by the flow of electrons from a negatively charged terminal to a positively charged terminal. This is because the electrons are repelled by the negatively charged terminal and attracted to the positively charged terminal. This movement of electrons is known as *electron flow*.

Figure 16.9 shows the difference between conventional current and electron flow.

Why are metals electrical conductors?

You have learnt previously that metals are electrical conductors. This is because the electrons in a piece of metal can leave their atoms and move about in the metal as *free electrons*. When connected to an energy source, these free electrons will be drove around the conducting path and a current is formed.

How do we measure electric current?

Since electric current is the flow of electric charges, we can measure electric current by determining the amount of electric charges that pass through a conductor per unit time.

One ampere is the electric current produced when one coulomb of charge passes a point in a conductor in one second.

Figure 16.10 *An analogue ammeter*

An **ammeter** (Figure 16.10) is used to measure the magnitude and direction of an electric current in an electric circuit.

The ammeter should be connected in series with the component whose current is to be measured (Figure 16.11). Conventional current flows into the ammeter through the positive '+' or red terminal and leave through the negative '–' or black terminal.

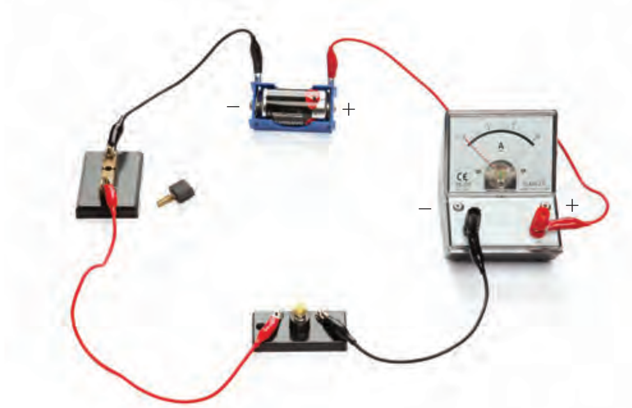


Figure 16.11 *An ammeter connected in series to measure the current I*

To measure current using the ammeter, we should take note of the following:

- It is important to get the correct range for the ammeter. When the current flowing through the ammeter is beyond the range of the ammeter, i.e. current is too large, the ammeter will be damaged. Therefore, ammeters have current ratings in which the largest current can be safely read.
- When the ammeter chosen has a rating that is too large for the current, the ammeter will not detect the current accurately. The meter reading will likely to be too close to zero for reading to be effective.
- Ammeters can be either analogue (with a moving needle) or digital (with a numerical readout that changes). Essentially, the primary difference between an analogue ammeter and a digital ammeter is the display.

LINK

You will learn more about series circuit in Chapter 17.

ENRICHMENT
THINK

The ampere is in fact defined more officially in terms of a magnetic force. Use the Internet to find out how the ampere is defined officially.

Share your answer with the class.

Alternating current and direct current

Electrical devices are designed to function with either **alternating current (a.c.)** or **direct current (d.c.)**. Direct current is used in electronic circuits and is supplied by batteries, cells and solar panels. Many mains supplies around the world provide alternating current. *Direct current flows in a single direction only, whereas alternating current changes direction frequently*.

Worked Example 16A

The current in a lamp is 0.2 A. If the lamp is switched on for two hours, what is the total electric charge that passes through the lamp?

Solution

Given: Current $I = 0.2$ A

$$\text{Time } t = 2\text{ h} \times \frac{60\text{ min}}{1\text{ h}} \times \frac{60\text{ s}}{1\text{ min}}$$
$$= 7200\text{ s}$$

$$I = \frac{Q}{t}$$

$$0.2\text{ A} = \frac{Q}{7200\text{ s}}$$

Total electric charge $Q = 0.2\text{ A} \times 7200\text{ s} = 1.4 \times 10^{-3}$ C

Let's Practise 16.3

1 S State the equation that relates electric charge to electric current.
2 S State the SI unit of current.
3 S Calculate how many electrons make a coulomb.
4 Describe how to use an ammeter.
5 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

Exercise 16C, pp. XX–XX

16.4 Electromotive Force and Potential Difference

In this section, you will learn the following:

- Define *electromotive force (e.m.f.)*
- Know that e.m.f. is measured in volts (V).
- S Recall and use the equation for e.m.f. $E = \frac{W}{Q}$.
- Define *potential difference (p.d.)*
- Know that the p.d. between two points is measured in volts (V).
- S Recall and use the equation for p.d. $V = \frac{W}{Q}$.
- Describe the use of voltmeters, analogue and digital, with different ranges.

How do currents occur?

In any complete circuit there must be an energy provider, often a battery or dry cell, and an energy user, such as a lightbulb or resistor.

The energy provider supplies the energy to drive a charge around the circuit. The work done by a source in moving a unit charge is known as the electromotive force or e.m.f. The e.m.f. is measured in **volts (V)**.

Electromotive force (e.m.f.) is the electrical work done by a source in moving a unit charge around a complete circuit.

In symbols, electromotive force is given by

$E = \frac{W}{Q}$ where E = e.m.f (in V);
W = work done (in J);
Q = charge (in C).

When a charge passes through a particular electrical component in the circuit, there is work done on the component. This work done per unit charge is known as the potential difference, or p.d. The p.d. between two points, i.e. across a component, is measured in **volts (V)**.

Potential difference (p.d.) is the work done by a unit charge passing through a component.

In symbols, potential difference is given by

$V = \frac{W}{Q}$ where V = p.d. (in V);
W = work done (in J);
Q = charge (in C).

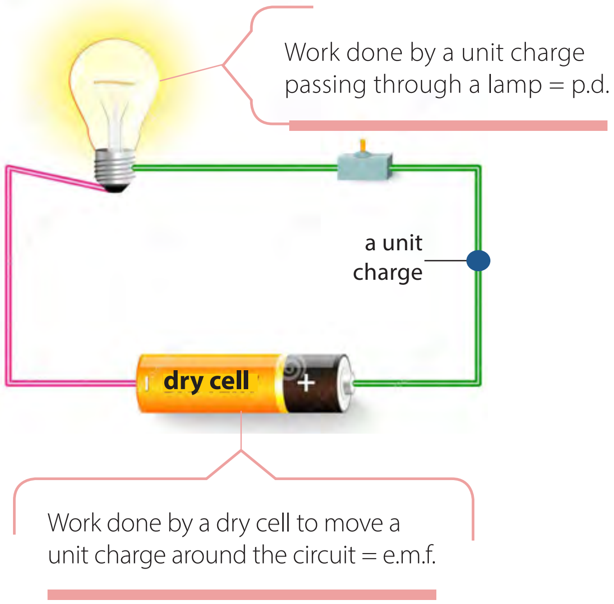


Figure 16.12 *Difference between e.m.f. and p.d.*

QUICK CHECK

The e.m.f. is a force.

True or false?

HELPFUL NOTES

Do not confuse e.m.f. and p.d., even though they have the same unit. The e.m.f. is provided by a source of electrical energy, but p.d. refers to the electrical energy converted to other forms by a circuit component.

How do we measure e.m.f. and p.d.?

A **voltmeter** (Figure 16.13) is used to measure the e.m.f. of a dry cell or the p.d. across a component.

The voltmeter should be connected *in parallel* with the dry cell or the component that is to be measured (Figure 16.14).

Figure 16.13 *An analogue voltmeter*

LINK

You will learn more about parallel circuit in Chapter 17.

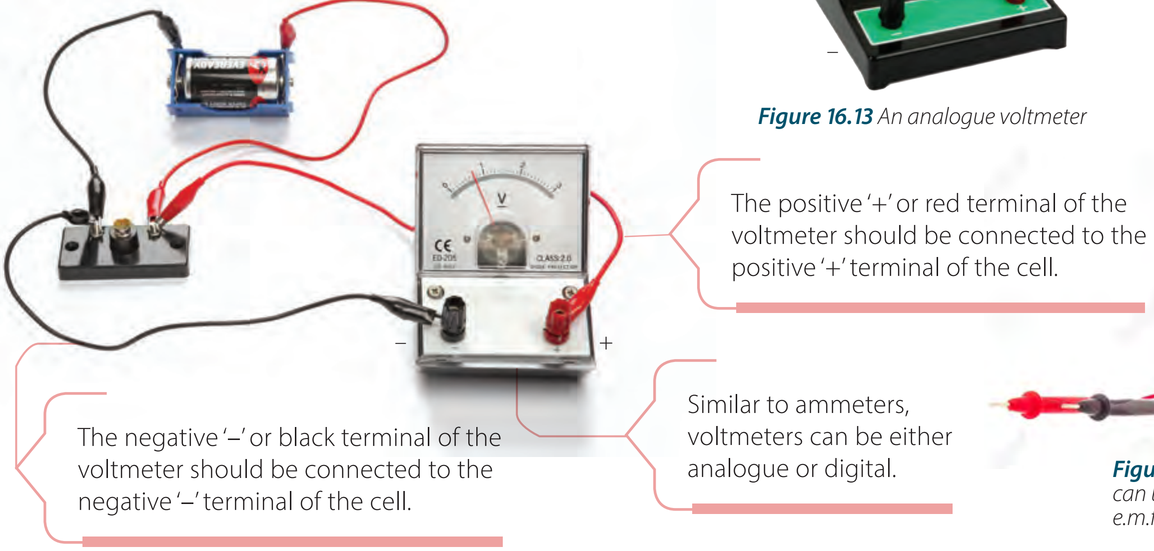


Figure 16.15 *A digital multimeter can be used to measure current, e.m.f. or p.d.*

Figure 16.14 *A voltmeter connected in parallel to measure the p.d. across the lamp*

ENRICHMENT INFO

Useful electric shocks

While electric shocks can kill, they can also be used to save lives. Have you ever seen defibrillators in public places (Figure 16.16)? A defibrillator is a device that can save the life of a person who is having a heart attack. It is connected to a power source and generates a potential difference so that an electric current flows through the heart. The heart is given a controlled electric shock to 'jolt it back to life' (i.e. to make it start pumping blood again).

Figure 16.16

Worked Example 16B

The e.m.f. of a dry cell is 1.5 V. What is the energy provided by the cell to drive 0.4 C of charge around a circuit?

Solution

Given: e.m.f. $E = 1.5$ V

charge $Q = 0.4$ C

Using $E = \frac{W}{Q}$, where W = energy provided by the cell,

$W = EQ$

$= (1.5 \text{ V})(0.4 \text{ C})$

$= 0.6$ J

Worked Example 16C

A charge of 4.00 x 10^4 C flows through an electric heater. If the amount of electrical energy converted into thermal energy is 9.00 MJ, calculate the potential difference across the ends of the heater.

Solution

Given: charge $Q = 4.00 \times 10^4$ C

energy $W = 9.00 \times 10^6$ J

By definition, potential difference $V = \frac{W}{Q}$

$= \frac{9.00 \times 10^6 \text{ J}}{4.00 \times 10^4 \text{ C}}$

$= 225$ V

Let's Practise 16.4

1 Describe the difference between e.m.f. and p.d.

2 The potential difference across a light bulb is found to be 3.0 V. The current flowing through it is 0.40 A.

(a) Calculate how much charge flows through the light bulb in 2.0 minutes.

(b) Calculate how much energy is dissipated by the charge calculated in (a).

3 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

Exercise 16D, pp. XX–XX

16.5 Resistance

In this section, you will learn the following:

- Recall and use the equation for resistance $R = \frac{V}{I}$.
- Describe an experiment to determine resistance using a voltmeter and an ammeter and do the appropriate calculations.
- (S) Sketch and explain the current-voltage graphs for a resistor of constant resistance, a filament lamp and a diode.
- (S) Recall and use the relationships for a metallic electrical conductor.
- State, qualitatively, the relationship of the resistance of a metallic wire to its length and to its cross-sectional area.

What is resistance?

Resistance is the measure of how difficult it is to pass an electric current through a conductor, such as a wire. When resistance is high, it is more difficult for charges to pass through the wire. Therefore, current will be reduced.

The **resistance** R of a component is the potential difference V across it divided by the current I flowing through it.

In symbols, the resistance of a component is given by

$$\boldsymbol{R = \frac{V}{I}}$$

where R = resistance of the component (in Ω)

V = p.d. across the component (in V)

I = current flowing through the component (in A)

From the definition of resistance, we can see that for a given p.d., the higher the resistance, the smaller the current passing through.

The SI unit of resistance is the **ohm (Ω)**. One ohm is the resistance of a component when a potential difference of one volt applied across the component drives a current of one ampere through it.

QUICK CHECK

The higher the resistance, the easier it is for current to flow.

True or false?

Worked Example 16D

A potential difference of 240 V applied across the heating coil of an electric kettle drives a current of 8 A through the coil. Calculate the

(a) resistance of the coil;

(b) new current flowing through the coil if the potential difference applied is changed to 220 V.

Solution

(a) Given: voltage $V = 240$ V

current $I = 8$ A

By definition, $R = \frac{V}{I} = \frac{240}{8} = 30\ \Omega$

(b) Given: voltage $V = 220$ V

From **(a)**, resistance $R = 30\ \Omega$.

Thus, $I = \frac{V}{R} = \frac{220}{30} = 7.3$ A

How do we measure resistance?

Circuit components such as wires and lamps have resistance. We can measure their resistances by measuring the current flowing through them and the p.d. across them. Figure 16.17 shows a current, I, flowing through a lamp and a potential difference, V, across it. With these two quantities, we can calculate the resistance of the lamp.

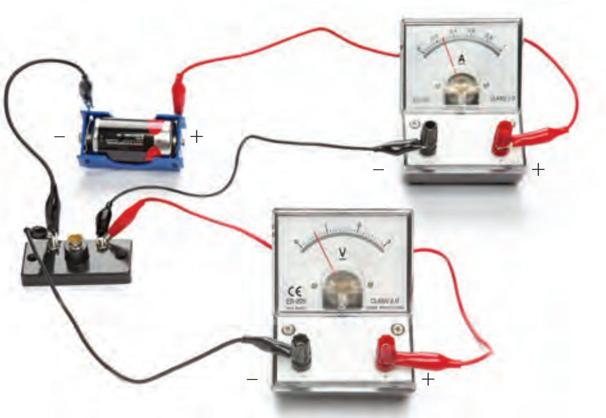


Figure 16.17 *Circuit to determine the resistance of a lamp*

Let's Investigate 16C

Objective

To determine the resistance of an ohmic resistor (which has low resistance) using a voltmeter and an ammeter

Materials

Voltmeter, ammeter, variable resistor, two 2 V dry cells, resistor R of unknown resistance

Procedure

1. Set up a circuit diagram as shown in Figure 16.18.
2. As a safety precaution, adjust the variable resistor to the maximum resistance. This is so that the initial current that flows in the circuit is small, to minimise the heating effect of the circuit.
3. Record the ammeter reading I and the voltmeter reading V.
4. Adjust the variable resistor to allow a larger current to flow in the circuit. Again, record the values of I and V.
5. Repeat step 4 to obtain at least five sets of I and V readings.
6. Plot V/V against I/A. Determine the gradient of the graph.

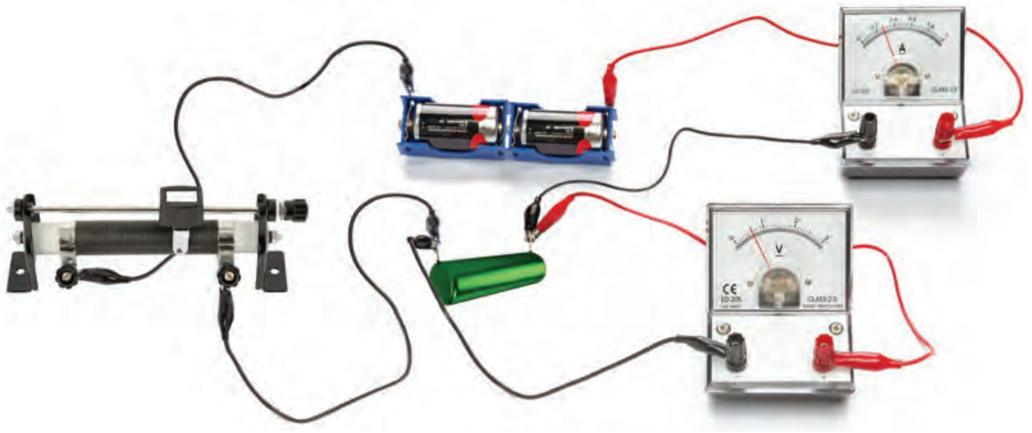


Figure 16.18

Observation and Discussion

The gradient of the graph gives the resistance of the resistor R (Figure 16.19). Note that the resistance of a conductor can be found using the gradient of the graph only if it is ohmic (i.e. it has a constant resistance).

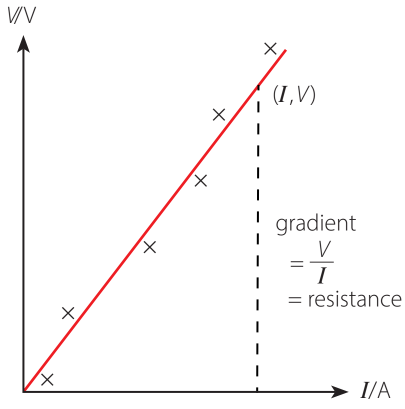


Figure 16.19

LINK

PWB

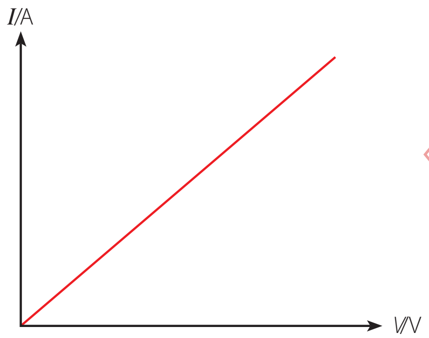
Practical 16C, pp. XX–XX

Ohm's Law

In 1826, German physicist Georg Ohm discovered that when physical conditions (such as temperature) are constant, the electric current in a metallic conductor is directly proportional to the potential difference across it. This relationship is known as *Ohm's Law*.

Ohm's Law states that the current passing through a metallic conductor is directly proportional to the potential difference across it, provided that physical conditions (such as temperature) remain constant.

According to Ohm's Law, the resistance of metallic conductors remains constant under steady physical conditions. Conductors that obey Ohm's Law are known as *ohmic conductors*. Figure 16.20 shows the characteristic I–V graph of an ohmic conductor at a constant temperature.



The graph
- is a straight line that passes through the origin;
- has a constant gradient that is equal to the inverse of the resistance R of the conductor.

Note: Since $\frac{1}{R}$ = constant, R = constant.

Figure 16.20 *Characteristic I–V graph of an ohmic conductor*

Conductors that do not Ohm's Law are known as *non-ohmic conductors*. The current flowing through non-ohmic conductors does not increase proportionally with the potential difference. In other words, the resistance R of such conductors can vary.

We can differentiate between ohmic and non-ohmic conductors using their I–V graphs. The I–V graphs of non-ohmic conductors are not straight lines. The $\frac{V}{I}$ ratio is not a constant, as non-ohmic conductors do not have constant resistances.

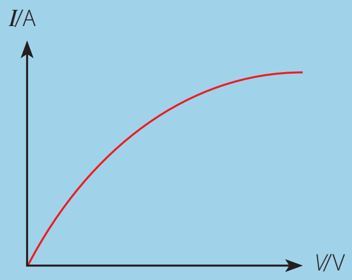
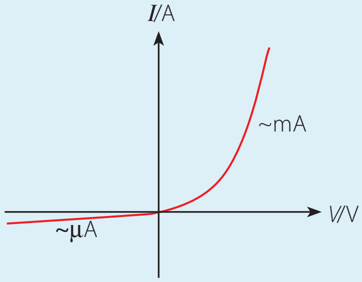
QUICK CHECK

Based on Ohm's law, current increases with increasing potential difference.

True or false?

Table 16.1 shows the characteristic curved I–V graphs of non-ohmic conductors.

Table 16.1 *Characteristic I–V graphs of some non-ohmic conductors.*

Non-ohmic conductor	Function	I–V graph	Description of graph
Filament lamp 	The filament lamp (or the light bulb) converts electrical energy to light and heat energy.		• As the currents increase, the devices generate more heat, and thus their temperatures increase. • As temperature increases, the resistance of the filament lamp increases. • The I–V graph of the filament lamp shows that the resistance $\left(\frac{V}{I}\right)$ increases with temperature.
Semiconductor diode 	A semiconductor diode is a device that allows current to flow in one direction only (the forward direction).		• The I–V graph of a semiconductor diode shows that when a p.d. is applied in the forward direction, the current flow is relatively large. This means the resistance is low in the forward direction. • When the p.d. is applied in the reverse direction, there is almost no current flow. This means the resistance is very high in the reverse direction.

Worked Example 16E

Figure 16.21 shows how the current I in the filament of a lamp depends on the potential difference V across it.

(a) Calculate the resistance of the filament when the potential difference is 1.0 V.

(b) Describe how the resistance of the filament changes, if at all, when the p.d. across it increases.

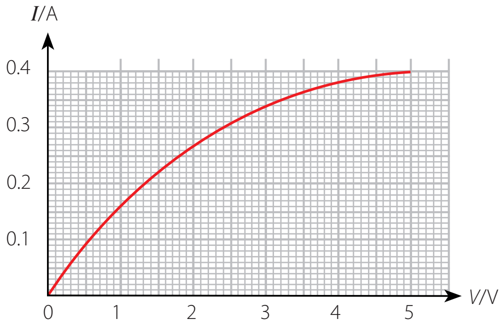


Figure 16.21

Solution

(a) From the graph, when $V = 1.0$ V, $I = 0.16$ A

By definition,

resistance $R = \dfrac{V}{I} = \dfrac{1.0\text{ V}}{0.16\text{ A}} = 6.25\ \Omega \approx 6.3\ \Omega$

(b) The gradient of the graph decreases as the p.d. increases. This means that the ratio $\dfrac{V}{I}$, which is the resistance R of the filament, increases when the p.d. across it increases.

HELPFUL NOTES

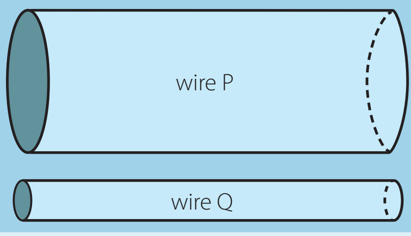
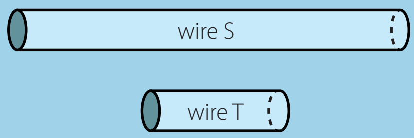
The SI unit of energy is the joule (J).

Resistivity

According to Ohm's Law, the resistance R of a metallic conductor is a constant if the physical conditions remain the same. However, if temperature increases, the resistance of the metallic conductor will also increase. Besides temperature, the resistance R of a conductor also depends on

- its length l;
- its cross-sectional area A (or thickness).

Table 16.2 *shows the relationship between resistance and the cross-sectional area and length of a wire.*

Relationship between resistance and cross-sectional area	Relationship between resistance and length
	
• Wires P and Q have the same length and are made of the same material. • The cross-sectional area of wire P is larger than that of wire Q. Experiments have shown that when the cross-sectional area of a wire is increased, its resistance decreases proportionally. In other words, the resistance R is inversely proportional to the cross-sectional area A when the length and type of material are the same.	• Wires S and T have the same cross-sectional area and are made of the same material. • Wire S is longer than wire T. Experiments have shown that when the length of a wire is increased, its resistance increases proportionally. In other words, the resistance R is directly proportional to the length l when the cross-sectional area and type of material are the same.

From Table 16.2, we can conclude the resistance of a metallic wire is

- directly proportional to its length;
- inversely proportional to its cross-sectional area.

Let's Practise 16.5

1 Ⓢ Describe how the resistance of the filament in a lamp varies with temperature.

2 Describe how the resistance of a wire varies with

(a) its length, and

(b) its cross-sectional area.

3 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

QUICK CHECK

The resistance of a conductor only depends on its length and cross-sectional area.

True or false?

PHYSICS WATCH

Scan this page to explore a simulation on resistivity.

LINK PWB

Practical 16D, pp. XX–XX

LINK TWB

Exercise 16E, pp. XX–XX

16.6 Electrical Energy and Electrical Power

In this section, you will learn the following:

- Understand that electric circuits transfer energy from a source of electrical energy to the circuit components and then into the surroundings.
- Recall and use the equation for electrical power $P = IV$.
- Recall and use the equation for electrical energy $E = IVt$.
- Define the kilowatt-hour (kW h) and calculate the cost of using electrical appliances where the energy unit is the kW h.

How does the energy get around?

Electric circuits transfer energy from a source of electrical energy such as the electrical cell or mains supply to the circuit components and then into the surroundings. Energy is transferred through the movement of electrons around *conducting materials* such as the lamps or resistors. In *insulating materials*, where electrons are not free to move about, there will not be electrical currents. When current flows through electrical components, energy will be dissipated in the form of heat, light or other energy. This energy is then transferred to the surrounding.

Electrical power

The SI unit of power is the **watt (W)**. One watt is equal to one joule per second. To represent large quantities of power, we often introduce prefixes such as kilo or mega. Therefore, large quantities of power are expressed in kilowatt or the megawatt.

Since power is the amount of work done per second, power P can be given by

$P = \frac{(W \text{ or } E)}{t}$ …(1) where P = power (in W)

W = work done (in J)

E = electrical energy converted (in J)

t = time (in s)

Earlier in this chapter, you have learnt the equations relating potential difference, work done, charge and current.

$I = \frac{Q}{t}$ …(2) where I = current (in A)

Q = charge (in C)

t = time (in s)

$V = \frac{W}{Q}$ V = potential difference (in V)

$W = QV$ …(3) W = work done (in J)

Substituting (3) into (1), we get

$P = \frac{QV}{t}$ …(4)

Since, $I = \frac{Q}{t}$ from (2),

$\boldsymbol{P = IV}$

We also know that from (1), the electrical energy E can be expressed as follows:

$\boldsymbol{E = Pt = IVt}$

HELPFUL NOTES

The SI unit of energy is the joule (J).

Calculating the cost of electricity consumption

An electricity meter measures a household's electricity consumption. The amount of electrical energy transferred to an appliance depends on its *power*, and on the duration of *time* it is switched on for. The joule is a tiny amount of energy and charging for each joule (or large numbers of joules) makes energy bills difficult to understand. Therefore, the kilowatt hour (kWh) is used as a unit of energy for calculating electricity bills.

1 kWh is the electrical energy converted by a 1 kW appliance used for 1 hour.

For example, a common household electrical heater has a power rating of approximately 2 kW. When it is being used for 1 hour, the energy consumption is 2 kW h. A filament lamp has a power rating of approximately 0.1 kW. When it is being used for 1 hour, the energy consumption is 0.1 kW h.

QUICK CHECK

The watt is the SI unit of power

True or false?

Worked Example 16F

If a power supply company charges 27 cents for each kW h of electrical energy used, calculate the total cost of using a 3 kW electric kettle for 20 minutes and a 100 W filament bulb for 5 hours.

Solution

Electrical energy used by electric kettle,

$E_1 = P \times t = 3\text{ kW} \times \frac{20}{60}\text{ h} = 1\text{ kW h}$

Power P of the filament bulb = 100 W = 0.1 kW

Electrical energy used by the bulb,

$E_2 = 0.1\text{ kW} \times 5\text{ h} = 0.5\text{ kWh}$

Total energy used $E = E_1 + E_2$

$= 1\text{ kWh} + 0.5\text{ kWh}$

$= 1.5\text{ kWh}$

Hence, the total cost = 1.5 kWh × 27 cents

= 40.5 cents

= \$0.41

Let's Practise 16.6

1 A 240 V mains power supply delivers a current of 9.0 A through an air conditioner. Calculate the power supplied in kilowatts.

2 The air conditioner in question **1** is used for 1.5 hours each day for 30 days. The electricity tariff is \$0.27 per kWh. Calculate the cost of using the air conditioner for this period of time.

3 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

TWB LINK

Exercises 16F–16G, pp. XX–XX

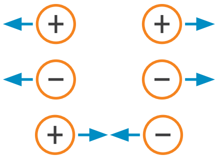
Exercise 16H Let's Reflect. p. XX

Let's Map It

CHARGE Q
(SI unit: C)

can be categorised into → **Positive and negative charges**

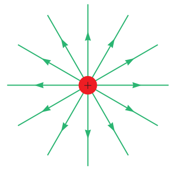
interacts as follows



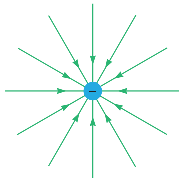
- Like charges repel
- Unlike charges attract

generates → **Electric field**

- Is a region in which an electric charge experiences a force



Electric field lines
- Directed away from a positive charge
- Directed towards a negative charge



moving charges produce → **Electric current I (SI unit: A)**

Electricity

Electrical *energy*
$E = IVt$

Power
$P = IV$

where
$I = \frac{Q}{t}$
where
t = time

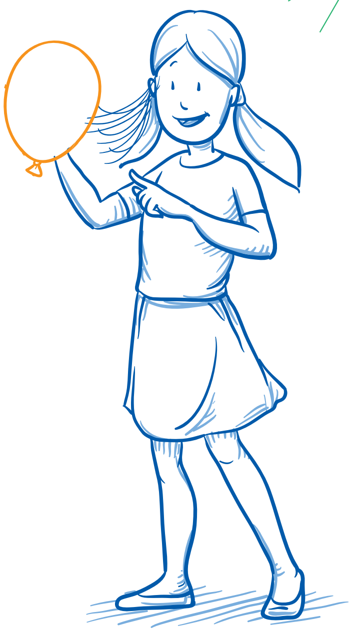
non-moving charges produce → **Static electricity**

is due to the build up of charges on the surfaces of

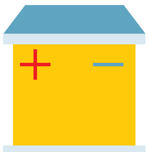
Electrical insulators

for example through

Friction



related to



Electromotive force E
(SI unit: V)

where

$E = \frac{W}{Q}$
where
W = work done by source to drive a unit charge around the circuit

Potential difference V
(SI unit: V)

where

$V = \frac{W}{Q}$
where
W = work done to drive a unit charge through a component

Related to

Resistance R
(SI unit: Ω)

- Resistance is directly proportional to the length of the conductor
- Resistance is inversely proportional to the cross-sectional area of the conductor

where

$R = \frac{V}{I}$

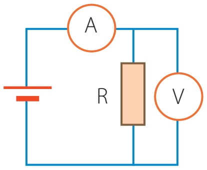
Let's Review

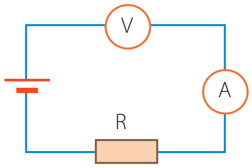
Section A: Multiple-choice Questions

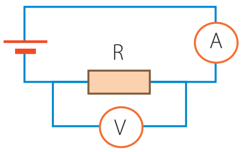
1 S A resistor converts 350 J of electrical energy to other forms of energy. What is the amount of charge that flows through it when a p.d. of 7 V is applied across it?

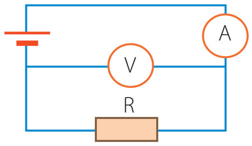
A 0.20 C
B 50 C
C 350 C
D 2450 C

2 Which of the following set-ups cannot be used to determine the resistance of resistor R?

A


B


C


D


3 The ammeter reading in the circuit below is 1 A. Which of the following could be the voltmeter reading and resistance of the resistor?

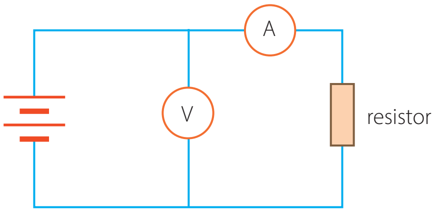


Figure 16.22

	Voltmeter reading	Resistance
A	1 V	2 Ω
B	4 V	0.25 Ω
C	10 V	10 Ω
D	12 V	6 Ω

4 Which of the following can be used to calculate electrical power?

A potential difference ÷ current
B potential difference × current
C current × resistance
D potential difference ÷ resistance

5 A small heater has a rating of 15 V, 4 A. How much energy does it consume if it is turned on for 2 minutes?

A 7.5 J
B 120 J
C 450 J
D 7200 J

6 The kilowatt-hour is a unit of _______.

A power
B energy
C charge
D voltage

7 A person uses a 3 kW oven for 1 hour and a 2 kW air conditioner for 6 hours. Calculate the total cost if 1 kWh of electrical energy costs 5.0 cents.

A 15 cents
B 30 cents
C 60 cents
D 75 cents

Section B: Short-answer and Structured Questions

1 Figure 16.23 shows the electrical information on the charger of a laptop computer.

Figure 16.23

(a) Based on the information in Figure 16.23, show that the output current of this charger is 4.74 A.

(b) Calculate the amount of electrical energy (in kWh) consumed in one month (30 days), if the laptop is connected to the charger 6 hours a day.

Let's Review

2 Two resistance wires, A and B, are connected in parallel to a power source of e.m.f. 5.0 V. Figure 16.24 shows the voltage–current relationship of the two wires.

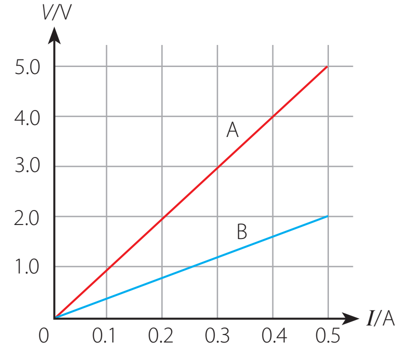


Figure 16.24

(a) Calculate the resistance of wire A and wire B.

(b) S If both wires are made of the same material and have the same thickness, what can you conclude about their lengths? Explain your answer.

(c) Calculate the currents flowing through wire A and wire B.

3 **(a)** S What is the relationship between current I and charge Q? State their respective SI units.

(b) S A positively-charged sphere carrying a charge of 0.4 mC is earthed using a wire.

(i) Calculate the average current flowing through the wire if the time taken to discharge the sphere is 0.2 s.

(ii) Draw a labelled diagram showing the direction of conventional current flow.

4 **(a)** What do you understand by the terms current and potential difference?

(b) S A potential difference of 12 V causes 2.0×10^{20} electrons to pass a point in awire in 1.0 minute. Calculate the

(i) amount of charge that passes the point in 1.0 minute, given that the charge of each electron is 1.6×10^{19} C;

(ii) electric current in the wire;

(iii) resistance of the wire.

5 A light bulb is connected to a 6.0 V e.m.f. supply. An experiment is carried out to measure the current flowing through the bulb as the potential difference across it is varied. The results are shown in Table 16.3.

Table 16.3

V/V	I/mA
0	0
1.0	0.5
2.0	1.1
3.0	1.6
4.0	2.1
5.0	2.5

(a) Plot a graph of potential difference against current, using the values from Table 16.3.

(b) Using the graph drawn in (a), determine the resistance of the bulb when the potential difference across it is 2.5 V.

(c) The 6.0 V e.m.f. supply is replaced with a 10.0 V e.m.f. supply.

(i) Determine the potential difference applied across the bulb if the current flowing through it is 0.32 mA.

(ii) Explain how it is possible for a 10.0 V e.m.f. supply to produce a current of 0.32 mA.

6 **(a)** The V–I graphs for two conductors, A and B, at a steady temperature are shown in Figure 16.25. Deduce the resistances of A and B.

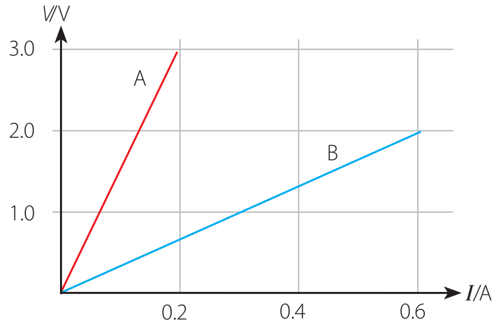


Figure 16.25

(b) S Both conductors are made of the same material and have the same length.

(i) Which conductor is thicker?

(ii) What is the ratio of their cross-sectional areas?

(c) Do the conductors A and B obey Ohm's Law? Explain your answer.

(d) S Sketch the graphs of current I against p.d. V for a

(i) filament lamp;

(ii) semiconductor diode.

CHAPTER

17

Electrical Circuits and Electrical Safety

PHYSICS WATCH

Scan this page to watch a clip on using electricity to light up our cities.

QUESTIONS

- What electrical components are needed in the electrical circuits to light up the city?
- What are some causes of power blackout in a city that are related to electrical circuits?
- What can be done to prevent such a power blackout?

The photo shows China's city of Shenzen at night during a light show. Complex electrical circuits are used to light up the buildings and streets. How did we progress from the first dim light bulbs to the amazingly colourful cityscapes we see today?

When the filament lamp was invented in the late 19th century, no one really knew how it would revolutionise the world the way it did. People could read, play, work, socialise and travel the streets in more relative safety. They don't have to rely on burning material and risk burning everything down to the ground.

17.1 Circuit Diagrams and Components

In this section, you will learn the following:

- Draw and interpret circuit diagrams containing common circuit components and know how these components behave in the circuit.
- S Draw and interpret circuit diagrams containing diodes and light-emitting diodes (LEDs) and know how these components behave in the circuit.

How to draw and interpret circuit diagrams?

Drawing circuit diagrams

To help us solve problems involving electric circuits, it is useful to learn how to draw circuit diagrams. Circuit diagrams represent electric circuits. Figure 17.1 shows the four main components of an electric circuit.

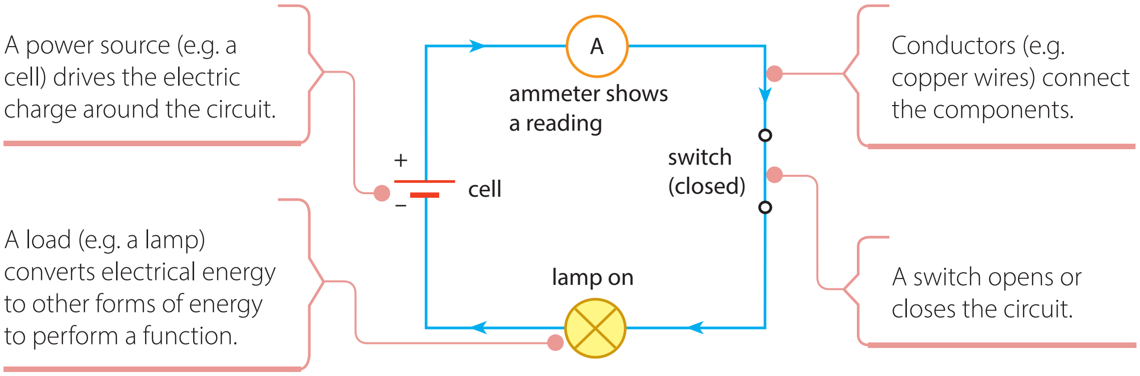


Figure 17.1 *Main components of an electric circuit*

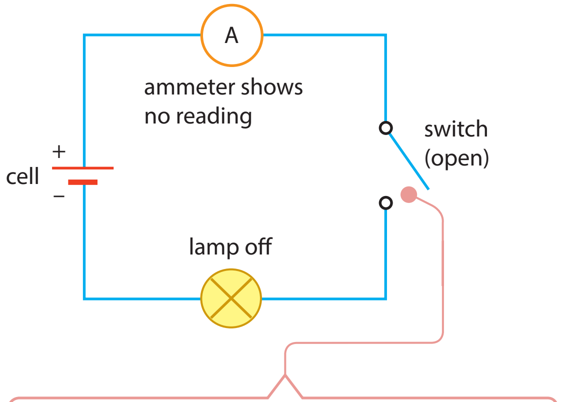
Table 17.1 shows the circuit symbols for some other common circuit components.

Table 17.1 *Circuit symbols*

Device	Symbol	Device	Symbol	Device	Symbol
Switch	or	Potential divider		Galvanometer	G
Cell	+ −	Fixed resistor		Ammeter	A
Battery	+ − or + −	Variable resistor (rheostat)		Voltmeter	V
D.c. power supply	+ −	Light-dependent resistor (LDR)		Generator	G
A.c. power supply	~	Fuse		Motor	M
Lamp		NTC thermistor		Heater	
Wires joined	or	Relay		Magnetising coil	
				S Diode	
Wires crossed		Transformer		S Light-emitting diode (LED)	

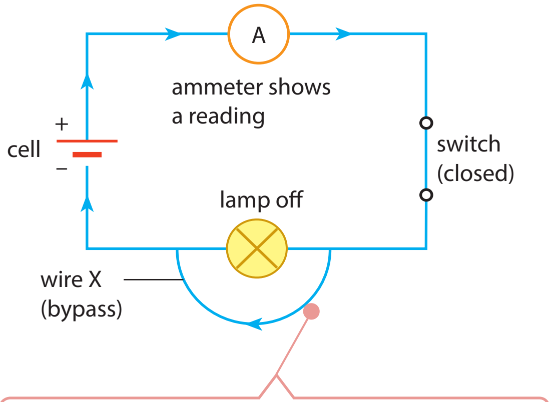
Interpreting circuit diagrams

It is important to be able to understand different arrangements of circuit symbols in circuit diagrams. Figures 17.2 and 17.3 show how we can interpret two circuit diagrams.



- The lamp is unable to light up as the switch is open, i.e., there is a break in the circuit.
- A break in the circuit means that current cannot flow through it.
- Besides open switches, breaks in circuits can occur due to loose connections, or missing or broken wires.

Figure 17.2 *Open circuit*



- The circuit is closed, yet the lamp remains unlit. This is because there is an alternative path of lower resistance (wire X) for current to flow through.
- Therefore, the current does not flow through the lamp.
- We call this a short circuit.

Figure 17.3 *Short circuit*

Circuit components are put to use for diverse purposes. Table 17.2 states the uses of some of these components. They are further described in various places in this chapter and the next.

Table 17.2 *Uses of some circuit components*

Component	Uses	See section
Potential divider	• Provide a fraction of a cell's e.m.f. to another part of a circuit • Can be used in sensing circuits	17.4
NTC thermistors	• Used as temperature sensors In temperature controlled circuits	17.4
Fuses	• For circuit safety	17.5
Generator	• Converts kinetic energy into electrical energy	18.2
Magnetising coil/relay	• Electromagnets and associated uses	18.3
Motors	• Converts electrical energy into kinetic energy	18.5
Transformer	• Transforms a potential difference to either a higher or lower potential difference with high efficiency	18.6

S

Why is a diode useful?

Some components, such as filament lamps, work equally well whether alternating current (a.c.) or direct current (d.c.) flows into them.

Other components, particularly many electronic parts, will only work with specific d.c. voltages and may break if subjected to a.c. voltages.

Diodes are components that allow current to flow through them in one direction only. Arrangements of diodes can indicate the direction of current flow so that appropriate action can be taken or can convert a.c. into d.c.

Current direction indication

Consider a dry cell which is connected to a light emitting diode (LED). Figure 17.4 shows how an arrangement of two diodes can show which direction the current is flowing. If the dry cell is connected in the first orientation, the green LED will light up. If the dry cell is reversed, then the red LED will light up.

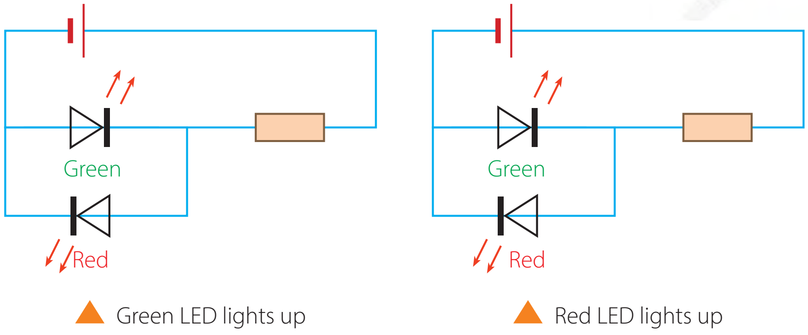


Figure 17.4 *LEDs indicate the direction of current flowing in a circuit*

A.c. rectification

Figure 17.5(a) shows a resistor connected to an a.c. power supply. The current-time graph below it shows the direction and magnitude of current through the resistor. In Figure 17.5(b)(i), the diode is the correct way around to allow current through. In Figure 17.5(b)(ii), the diode will not allow current to flow as shown by the horizontal lines in the graph below it. If a component in an electrical circuit is sensitive to current direction, the presence of a diode protects the component.

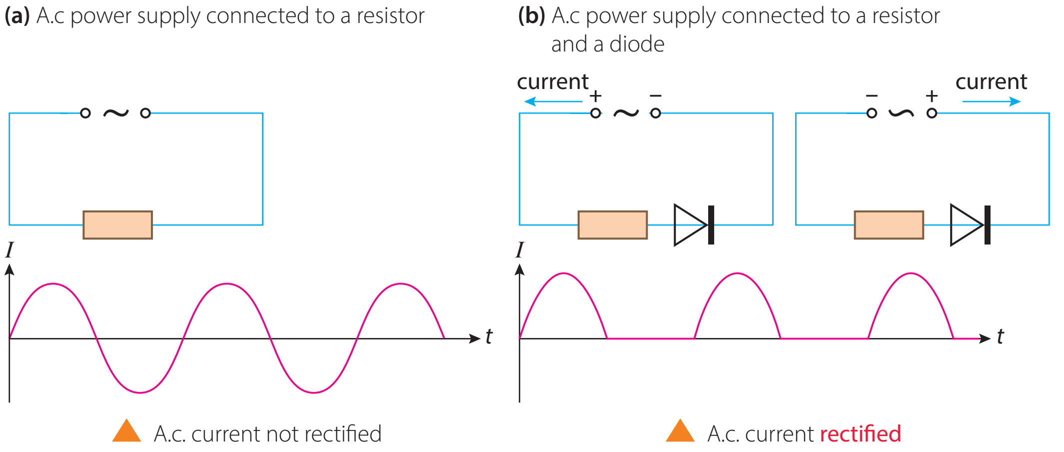


Figure 17.5 *Rectified and unrectified a.c. current*

ENRICHMENT THINK

This method of a.c. rectification is wasteful as the current is only useful for 50% of the time. It is known as *half-wave rectification*. The rest of the time, the energy is merely dissipated as heat.

How could an arrangement of four diodes provide *full-wave rectification*, so that the design is more efficient?

WORD ALERT

Rectified: to set right, i.e., setting the current to flow in one direction

LINK

Exercise 17A, pp. XX-XX

Let's Practise 17.1

1. Describe what is meant by an open circuit.
2. Ⓢ Describe the basic function of a diode.
3. Ⓢ Draw an electrical circuit that lights
   (a) a red LED when current is flowing in one direction around the circuit;
   (b) a green LED when current flows in the opposite direction.
4. Ⓢ Explain a use of diodes in a practical circuit.
5. **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

17.2 Series Circuits

In this section, you will learn the following:

- Know how to construct and use series circuits.
- Calculate the combined e.m.f. of several sources in series.
- Know that the current at every point in a series circuit is the same.
- S Explain that the sum of the currents into a junction is the same as the currents out of the junction.
- S Recall and use in calculations, the fact that the total p.d. across the components in a series circuit is equal to the sum of the individual p.d.s across each component.
- Calculate the combined resistance of two or more resistors in series.

In this chapter, you will learn how series and parallel arrangements of circuits affect current, potential difference and resistance.

In a **series circuit**, the components are connected one after another in a single loop (Figure 17.6). A series circuit has only one path through which electric charge can flow.

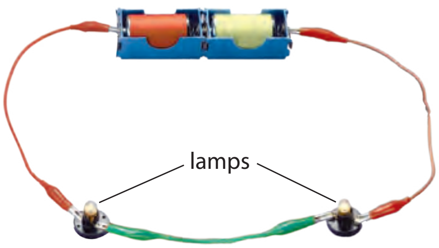


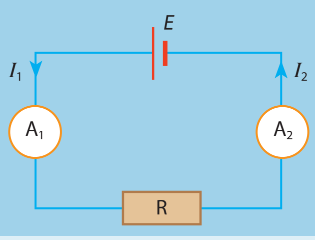
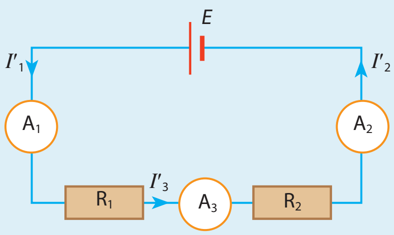
Figure 17.6 *Two lamps connected in series*

Notice that in Figure 17.6 there are two dry cells in series. When cells are arranged in series, the resultant e.m.f. is the sum of all the e.m.f.s of the cells. For example, if both cells in Figure 17.6 had an e.m.f. of 1.5 V, then the combined e.m.f. would be 3.0 V.

Does current in a series circuit change?

Table 17.3 shows two electric circuits that can be set up to measure the current at various points in a series circuit.

Table 17.3 *Current in series circuits*

Circuit	Ammeter reading	Conclusion
Single resitor R 	$I_1 = I_2$	The same current flows into and out of resistor R.
Resistors R_1 and R_2 in series 	$I'_1 = I'_2 = I'_3$	The same current flows through R_1 and R_2.

HELPFUL NOTES

The currents in the two circuits in Table 17.3 are not the same. They will be the same if $R = R_1 + R_2$. You will learn the effect of combining resistors in series later.

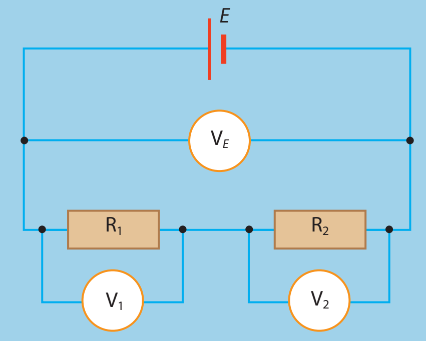
We can see that *the current at every point in a given series circuit is the same*.

S No charge can escape or be introduced at any point in the circuit. This is known as the *conservation of charge*. It explains why the current through components in series must be the same.

How to calculate total p.d across a series circuit?

Table 17.4 shows an electric circuit in which the resistors are arranged in series. It is set up to measure the potential difference across the resistors in the circuit.

Table 17.4 *P.d. across resistors in a series circuit.*

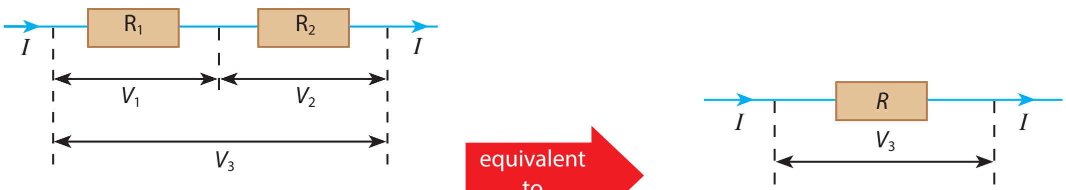
Circuit	Ammeter reading	Conclusion
Resistors R_1 and R_2 in series 	$V_E = V_1 + V_2$	The p.d. V_E across the whole circuit is equal to the sum of the p.d.s across R_1 and R_2.
	$E = V_E$	The e.m.f. E of the electrical source is equal to V_E.

For n resistors placed in series, the p.d. V_E across the whole circuit (i.e. across all of the components) is equal to the sum of the p.d.s across each component.

$\boldsymbol{V_E = V_1 + V_2 + \ldots + V_n}$

How to calculate combined resistance in series?

Figure 17.7 shows how we can find the combined or effective resistance R of two resistors, R_1 and R_2, that are connected in series.



Resistors in series

Equivalent resistor

- The current I that flows through R_1 and R_2 is the same because they are connected in series.
- Since $V = IR$, $V_1 = IR_1$
  $V_2 = IR_2$
- From the equation $V_E = V_1 + V_2$, we know that
  $V_3 = V_1 + V_2 = IR_1 + IR_2 = I(R_1 + R_2)$
  Therefore, $\frac{V_3}{I} = R_1 + R_2$.

- The resistors R_1 and R_2 can be replaced by a single resistor R with a resistance R.
- The resistor R has the potential difference or voltage V_3 across it and the current I flowing through it.
  $\frac{V_3}{I} = R$

$R = R_1 + R_2$

Figure 17.7 *Combined resistance of resistors in series*

For n resistors in placed in series, the combined resistance is the sum of all the resistances.

$\boldsymbol{R = R_1 + R_2 + \ldots + R_n}$

Worked Example 17A

Figure 17.8 shows three resistors of values 2 Ω, 4 Ω and 6 Ω connected in series to a 6 V dry cell.

(a) Calculate the combined resistance of the three resistors.

(b) What is the current measured by **(i)** ammeter A_1; **(ii)** ammeter A_2?

(c) Calculate the p.d. across each resistor.

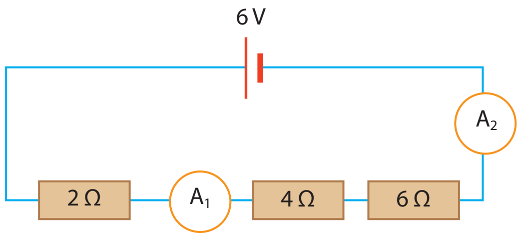


Figure 17.8

Solution

(a) Combined resistance $R = R_1 + R_2 + R_3 = (2 + 4 + 6)\ \Omega = 12\ \Omega$

(b) **(i)** Since V = 6 V and combined resistance $R = 12\ \Omega$,

$$I = \frac{V}{R} = \frac{6\text{ V}}{12\ \Omega} = 0.5\text{ A}$$

The current measured by ammeter A_1 is 0.5 A.

(ii) Since the circuit is connected in series, the current measured by ammeter A_2 is also 0.5 A.

(c) Let V_1, V_2 and V_3 be the p.d.s across the 2 Ω, 4 Ω and 6 Ω resistors respectively.

Using $V = IR$,

$V_1 = IR_1 = 0.5\text{ A} \times 2\ \Omega = 1\text{ V}$

$V_2 = IR_2 = 0.5\text{ A} \times 4\ \Omega = 2\text{ V}$

$V_3 = IR_3 = 0.5\text{ A} \times 6\ \Omega = 3\text{ V}$

Note: (1) $V_1 + V_2 + V_3 = 6\text{ V}$ = e.m.f. of the cell

(2) The p.d. across a resistor of a larger resistance in a series circuit is greater than the p.d. across a resistor of a smaller resistance.

QUICK CHECK

The combined resistance of resistors in series is the sum of all of the resistances.

True or false?

17.3 Parallel Circuits

In this section, you will learn the following:

- Know how to construct and use parallel circuits.
- State that, for a parallel circuit, the current from the source is larger than the current in each branch.
- S Recall and use in calculations, the fact that the sum of the currents into a junction in a parallel circuit is equal to the sum of the currents that leave the junction.
- S Recall and use in calculations, the fact that the p.d. across an arrangement of parallel resistors is the same as the p.d. across one branch in the arrangement of the parallel resistors.
- S Calculate the combined resistance of two resistors in parallel.
- State that the combined resistance of two resistors in parallel is less than that of either resistor by itself.
- State the advantages of connecting lamps in parallel in a lighting circuit.

In a **parallel circuit**, the components are connected to the e.m.f. source in two or more loops (Figure 17.9). A parallel circuit has *more than one path through which electric charge can flow*.

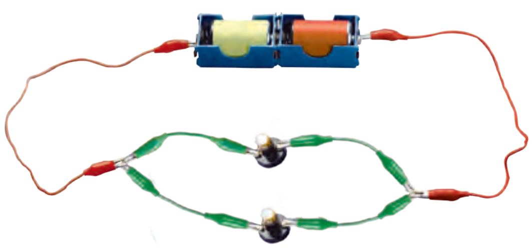


Figure 17.9 *Two lamps connected in parallel*

QUICK CHECK

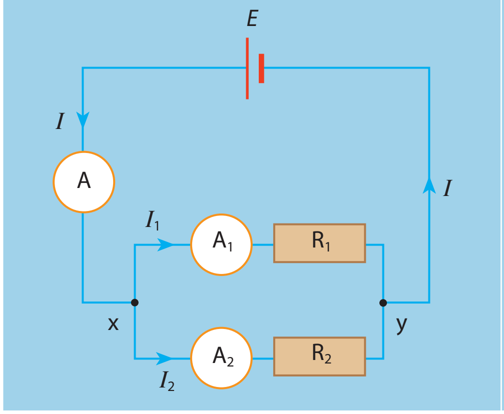
The current is the same at different points of a parallel circuit.

True or false?

How does current flow in a parallel circuit?

Table 17.5 shows an electric circuit in which the resistors are arranged in parallel. It is set up to measure the current at various points in the circuit.

Table 17.5 *Currents at various points of a parallel circuit*

Circuit	Ammeter reading	Conclusion
Resistors R_1 and R_2 in parallel 	$I = I_1 + I_2$	• The current I flowing from the cell splits at junction x into I_1 and I_2. • Currents I_1 and I_2 later recombine into I at junction y.

We can see that *the current from the source is larger than the current in each branch*.

For *n* branches in parallel, the main current I is the sum of all the currents in each branch.

$I = I_1 + I_2 + \ldots + I_n$

LINK

Recall that $Q = It$ and so $I = \frac{Q}{t}$.

Refer to Chapter 16.

S

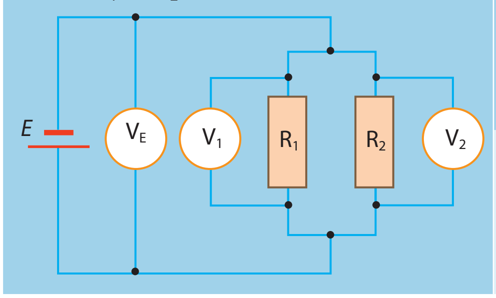
In other words, in a parallel circuit, the sum of the individual current in each of the parallel branches is equal to the main current flowing into or out of the parallel branches. This is because charge is conserved and current is the rate of flow of charge. When a number of electrons enter junction x, the same number of electrons must leave junction x. Similarly, when a number of electrons enter junction y, the same number of electrons must leave junction y.

Does p.d across a parallel circuit change?

Table 17.6 shows an electric circuit in which all the resistors are arranged in parallel. It is set up to measure the p.d across each resistor, and the p.d. across all the resistors in the circuit.

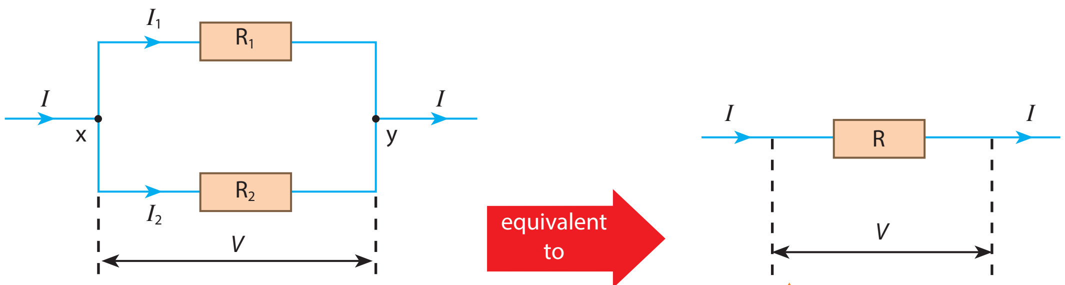
In a parallel circuit, the p.d.s across separate parallel branches are the same.

Table 17.6 *P.d across resistors in a paralle circuit*

Circuit	Ammeter reading	Conclusion
Resistors R_1 and R_2 in series 	$V_E = V_1 = V_2$	The p.d. V_E across the whole circuit is equal to the sum of the p.d.s across R_1 and R_2.
	$E = V_E$	The e.m.f. E of the electrical source is equal to V_E.

How to calculate combined resistance in parallel?

Figure 17.10 shows how we can find the combined resistance R of two resistors, R_1 and R_2, that are connected in parallel.



Resistors in parallel

- The current I is split into I_1 and I_2 because R_1 and R_2 are connected in parallel.
- Since $I = \frac{V}{R}$, $I_1 = \frac{V}{R_1}$
  $I_2 = \frac{V}{R_2}$
- From the equation $I = I_1 + I_2$, we know that
  $I = \frac{V}{R_1} + \frac{V}{R_2}$

Equivalent resistor

- The resistors R_1 and R_2 can be replaced by a single resistor R with a resistance R.
- The resistor R has the p.d. V across it and the current I flowing through it.
  $I = \frac{V}{R}$

$$\frac{V}{R} = \frac{V}{R_1} + \frac{V}{R_2}$$
$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

Figure 17.10 *Combined resistance of resistors in parallel*

For two resistors in parallel,

$$\mathbf{\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}}$$

In other words, the **reciprocal** of the combined resistance of resistors in parallel, $\frac{1}{R}$, is equal to the sum of the reciprocal of all the individual resistances.

WORD ALERT

Reciprocal: the reciprocal of a number is obtained by dividing 1 by that number

Worked Example 17B

Figure 17.11 shows three resistors of values 3 Ω and 6 Ω connected in parallel to a 6 V dry cell.

(a) Calculate the combined resistance of the two resistors.

(b) What is the p.d. across each resistor?

(c) What is the current measured by ammeters A_1 and A_2?

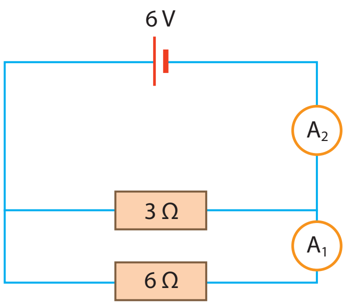


Figure 17.11

Solution

(a) $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{3\,\Omega} + \frac{1}{6\,\Omega} = \frac{3}{6\,\Omega}$

$\therefore R = 2\,\Omega$

QUICK CHECK

A circuit with just a resistor and a dry cell has a current of 1.2 A.

A second resistor is put in parallel with the first. The current through the dry cell remains the same.

True or false?

HELPFUL NOTES

Parallel connections can be represented in different ways in a circuit diagram. For example, a voltmeter connected in parallel with a circuit component (e.g. a cell) can be represented in the two ways shown in Figure 17.13.

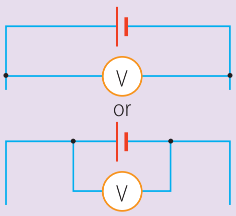


Figure 17.13 *Representing a voltmeter connected in parallel with a cell*

(b) As the resistors are in parallel, the p.d. across each resistor is equal, i.e., 6 V.

Using $I = \frac{V}{R}$,

Current through the 6 Ω resistor $= \frac{6\text{V}}{6\ \Omega} = 1\text{ A}$

Current measured by ammeter $A_1 = 1\text{ A}$

Current through the 3 Ω resistor $= \frac{6\text{V}}{3\ \Omega} = 2\text{ A}$

Current measured by ammeter $A_2 = 2\text{ A} + 1\text{ A} = 3\text{ A}$

Alternatively, since $V = 6$ V and combined resistance $R = 2\ \Omega$, current measured by ammeter $A_2 = \frac{6\text{ V}}{2\ \Omega} = 3\text{ A}$

How can two resistors in parallel have less resistance than one resistor?

When another resistor is added in parallel to a resistor in a circuit, the combined resistance of the circuit *decreases*. It is *less than the resistance of either resistor by itself*. We can explain this using Figure 17.12. In a parallel circuit, the p.d. remains the same across each branch. When R_2 is connected in parallel to R_1, as shown in Figure 17.12, the current I in the circuit increases by I_2 (since $I = I_1 + I_2$).

The combined resistance $R \left(= \frac{V_E}{I}\right)$ therefore decreases. Connecting additional resistors in parallel to R_1 and R_2 further increases the current I. Thus, the combined resistance R is lowered.

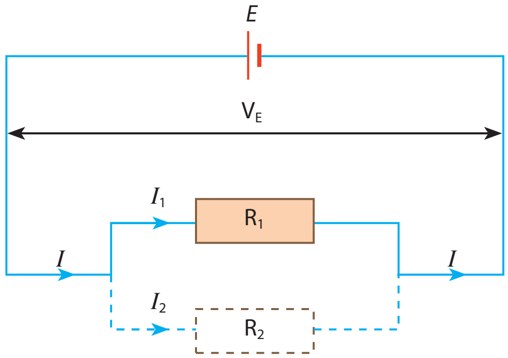
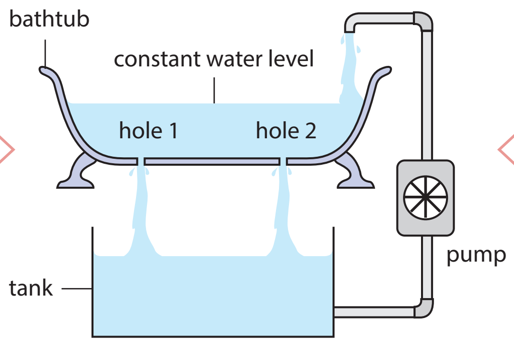


Figure 17.12 *Connecting an additional resistor in parallel to R_1 provides an additional path for the current to flow. Thus, the combined resistance is lowered.*

To understand the flow of current in a parallel circuit better, we can use the water-flow model (Figure 17.14), in which the

- flow of water represents current;
- water level in the bathtub represents potential difference;
- pump represents an electrical source.

- When hole 1 is unplugged, water flows out slowly.
- The pump is turned on to maintain a constant level of water in the bathtub.
- This is similar to an electrical source driving a current through a single resistor in a circuit.



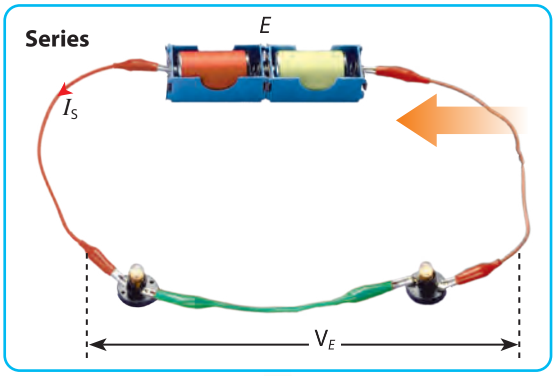
- When holes 1 and 2 are unplugged, water flows out of the bathtub faster.
- The pump has to work faster to maintain the level of water in the bathtub.
- This is similar to an electrical source which is connected to two resistors in parallel in a circuit. The electrical source has to provide a larger power to drive a larger current to maintain the p.d.

Figure 17.14 *The water-flow model can represent current flow in a parallel circuit.*

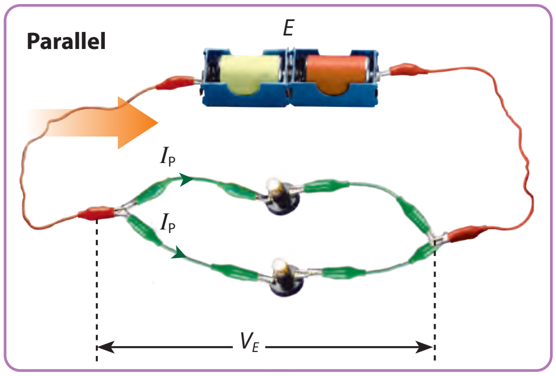
So, in this model, having two holes in the bathtub means that the flow of water has increased. Thus, in a parallel electric circuit, the combined resistance must have decreased to cause a larger current flow for the same e.m.f.

Connecting lamps in series or parallel

What are the advantages of arranging circuit components in series or in parallel? To answer this question, let us consider the effects of different lamp arrangements on current (Figure 17.15). The lamps shown in Figure 17.15 are identical and each have a resistance of R.



When identical lamps are arranged in



Series		Parallel
	the potential difference across	
each lamp is $\frac{V_E}{2}$		each lamp is V_E
	the effective resistance of	
each lamp is R		each lamp is R
	∴ The current flowing through each lamp is	
$I_S = \frac{V_E/2}{R} = \frac{1}{2}\left(\frac{V_E}{R}\right)$		$I_P = \frac{V_E}{R}$

Figure 17.15 *Current in series and parallel arrangements*

What are the advantages and disadvantages of parallel circuits?

Advantages

- From Figure 17.15, it can be seen that the current flowing through each lamp in the series circuit is half that of the current flowing through each lamp in the parallel circuit. Therefore, lamps connected in parallel glow more brightly than when connected in series.
- When a lamp in a parallel circuit **blows**, the other lamps in the circuit will still work. This is because each parallel branch forms a complete circuit.

Disadvantages

- From Figure 17.15, it can be seen that the current flowing through the battery in the parallel circuit is $2I_P$, which is four times the current I_s in the series circuit. This means that the source in a parallel circuit provides a larger power and is **depleted** more quickly than in a series circuit.

WORD ALERT

Blows: burns out
Depleted: used up

Resistors in series and parallel in a circuit

The electric circuits in electrical devices typically have resistors in both series and parallel arrangements. How do we calculate the combined resistance? How do we find the current and p.d. across each resistor? The following worked examples will show us how.

Worked Example 17C

Calculate the combined resistance of the arrangements in Figures 17.16 and 17.17.

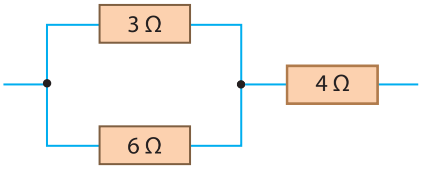


Figure 17.16

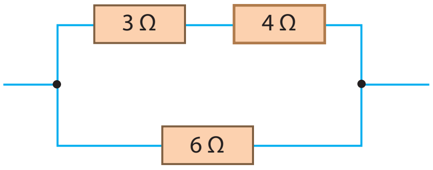


Figure 17.17

Solution

For Figure 17.16, the 3 Ω and 6 Ω resistors are in parallel.

Therefore, $\frac{1}{R} = \frac{1}{3\,\Omega} + \frac{1}{6\,\Omega} = \frac{3}{6\,\Omega}$. Their combined resistance $R = 2\,\Omega$.

Now, consider the circuit as comprising a 2 Ω resistor and a 4 Ω resistor in series (Figure 17.18).

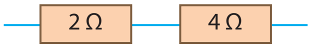


Figure 17.18

Hence, the combined resistance $R_T = 2\,\Omega + 4\,\Omega = 6\,\Omega$.

For Figure 17.17, the 3 Ω and 4 Ω resistors are in series.

Therefore, their combined resistance is $R = 3\,\Omega + 4\,\Omega = 7\,\Omega$.

Now, consider the circuit as comprising a 7 Ω resistor and a 6 Ω resistor in parallel (Figure 17.19).

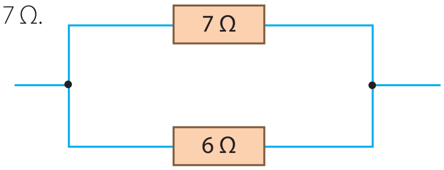


Figure 17.19

Hence, $\frac{1}{R_T} = \frac{1}{7\,\Omega} + \frac{1}{6\,\Omega} = \frac{13}{42\,\Omega}$.

The combined resistance $R_T = 3.2\,\Omega$.

Worked Example 17D

The cell in Figure 17.20 has an e.m.f. of 6 V. Calculate the

(a) combined resistance of the two resistors connected in parallel;

(b) current I_1 from the cell;

(c) p.d.s across XY and YZ;

(d) currents I_2 and I_3.

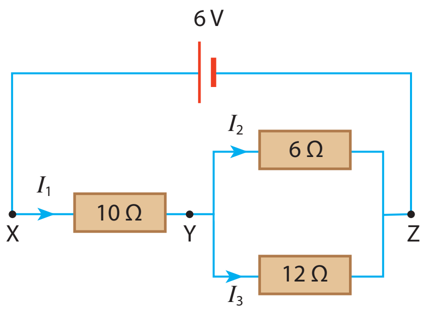


Figure 17.20

Solution

(a) Since the 6 Ω and 12 Ω resistors are in parallel, their combined resistance R is

$$\frac{1}{R} = \frac{1}{6\,\Omega} + \frac{1}{12\,\Omega}$$

$$R = \left(\frac{1}{6} + \frac{1}{12}\right)^{-1}\,\Omega = 4\,\Omega$$

(b) Now, consider the circuit as comprising a 10 Ω resistor and a 4 Ω resistor in series (Figure 17.21).

$\therefore$ The combined resistance R_T
$= 10\ \Omega + 4\ \Omega = 14\ \Omega$

Since the e.m.f. $E = 6$ V,

the current $I_1 = \dfrac{V}{R_T} = \dfrac{6\text{V}}{14\ \Omega} = 0.43$ A

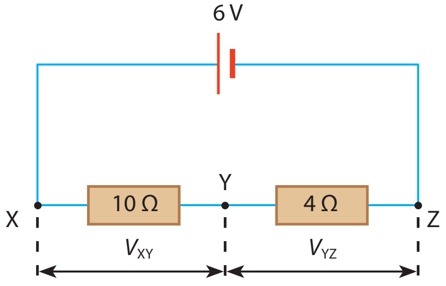


Figure 17.21

(c) Let R_1 be the 10 Ω resistor.

Since $I_1 = 0.43$ A, then p.d. across XY is

$V_{XY} = I_1R_1 = 0.43\text{ A} \times 10\ \Omega = 4.3$ V

Since the circuit in Figure 17.20 is connected in series,

e.m.f. $E = V_{XY} + V_{YZ}$

$\therefore V_{YZ} = E - V_{XY} = 6\text{ V} - 4.3\text{ V} = 1.7$ V

(d) Since $V_{YZ} = 1.7$ V,

$I_2 = \dfrac{V_{YZ}}{R_2} = \dfrac{1.7\text{ V}}{6\ \Omega} = 0.28$ A

$I_3 = \dfrac{V_{YZ}}{R_3} = \dfrac{1.7\text{ V}}{12\ \Omega} = 0.14$ A

PWB LINK

Practical 17, pp. XX–XX

Let's Practise 17.2 and 17.3

1 Figure 17.22 shows a 5 V cell connected to two resistors in parallel. The current flowing through resistor R is 0.2 A. Calculate

(a) the resistance of resistor R;

(b) the currents I_1 and I_2;

(c) S the combined resistance of resistor R and the 50 Ω resistor;

(d) the combined resistance of resistor R and the 50 Ω resistor if they are arranged in series instead.

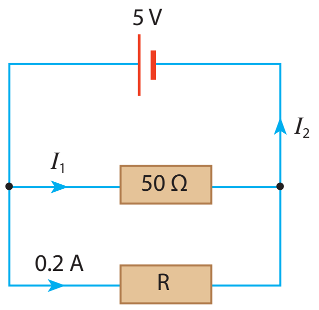


Figure 17.22

2 State **one** major advantage of connecting lamps in parallel.

3 S A number of 4 Ω resistors are available. Draw diagrams to show how you can connect a suitable number of these resistors to give a combined resistance of

(a) 12 Ω; **(b)** 2 Ω; **(c)** 9 Ω.

4 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

TWB LINK

Exercise 17B, pp. XX-XX

17.4 Action and Use of Circuit Components

In this section, you will learn the following:

- Know that the p.d. across an electrical conductor increases as its resistance increases for a constant current.
- S Recall and use the equation for two resistors used as a potential divider: $\dfrac{R_1}{R_2} = \dfrac{V_1}{V_2}$
- S Describe the action of a variable potential divider.
- Recall what is Ohm's Law which you have learnt in Chapter 16.

LINK

Recall what is Ohm's Law which you have learnt in Chapter 16.

The p.d. across a conductor (such as a resistor or lamp) *increases as its resistance increases, provided that the current is constant*. This is a consequence of Ohm's Law. The use of potential dividers makes use of this concept.

What is a potential divider and how does it work?

Some electronic circuits, such as those found in radios and battery-operated toys, require an e.m.f. that is much smaller than that provided by a single cell. Potential dividers can be used to adjust voltages in these circuits.

A **potential divider** is a line of resistors connected in series. It is used to provide a fraction of the available p.d. from a source to another part of the circuit.

S

Figure 17.23 shows a potential divider with two fixed resistors. The cell supplies a voltage V_E that is divided into two potential differences across the resistors R_1 and R_2. The potential difference V_{out} across R_2 is then used to drive another part of the circuit.

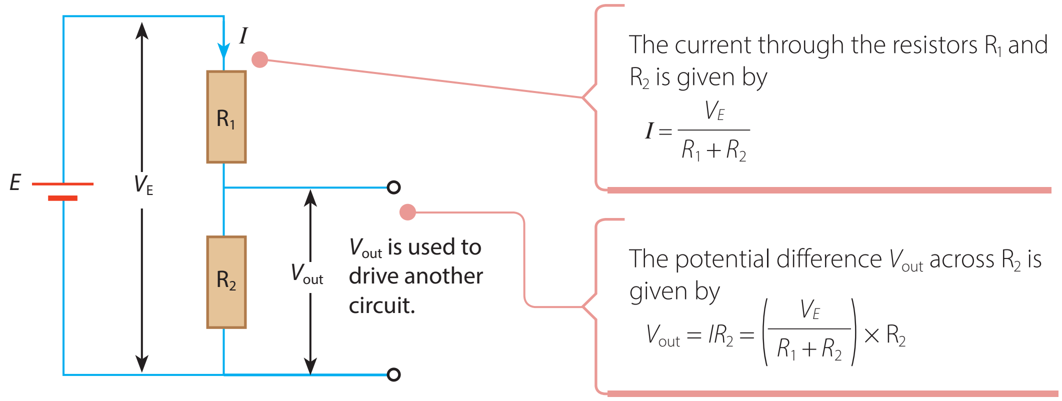


Figure 17.23 *Calculating V_{out} in a simple potential divider*

ENRICHMENT THINK

Show how these two equations:

$V_{out} = \left(\frac{R_2}{R_1 + R_2}\right) \times V_E$

and $\frac{R_1}{R_2} = \frac{V_1}{V_2}$ are equivalent.

The equation for V_{out} in Figure 17.23 can be rewritten as

$V_{out} = \left(\frac{R_2}{R_1 + R_2}\right) \times V_E$ or as

$\boldsymbol{\frac{R_1}{R_2} = \frac{V_1}{V_2}}$ where V_1 = p.d. across R_1 and V_2 = p.d. across R_2

From the above equation, we can see that the output p.d. V_{out} across R_2 is a fraction of the input p.d. V_E.

Worked Example 17E

What is the output voltage across the 20 Ω resistor in Figure 17.24?

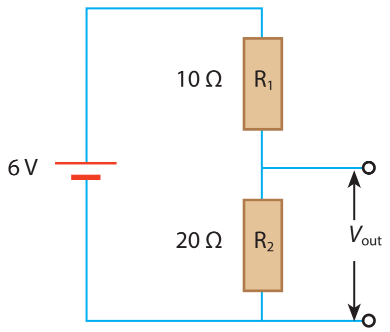


Figure 17.24

Solution

Given: $V_E = 6$ V, $R_1 = 10$ Ω, $R_2 = 20$ Ω

$$V_{out} = \left(\frac{R_2}{R_1 + R_2}\right) \times V_E = \left(\frac{20}{20 + 20}\right) \Omega \times 6\text{ V} = 4\ \Omega$$

Hence, the output voltage $V_{out} = 4$ V.

How are potential dividers useful?

Potential dividers that are used to *vary* the output voltage from a source are called **variable potential dividers**. They are used in electrical devices, such as stereo systems to vary the output voltage, and thus control the volume of the sound.

Variable potential dividers make use of variable resistors. Methods 1 and 2 show how two types of variable potential dividers are used to obtain a variable output voltage V_{out}.

Method 1

- This type of variable potential divider makes use of a rheostat R_1 (Figure 17.25). A **rheostat** is a variable resistor that is connected at two terminals.
- Since $V_{out} = \left(\dfrac{R_2}{R_1 + R_2}\right) \times V_E$, this means that when the resistance R_1 increases, the output voltage V_{out} decreases.
- To obtain a larger output voltage, the resistance R_1 should be decreased.

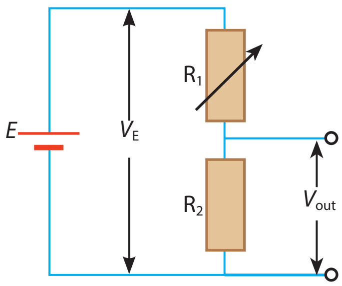


Figure 17.25 *A rheostat being used in a variable potential divider*

Method 2

- This type of variable potential divider makes use of a potentiometer (Figure 17.26). A **potentiometer** is a variable resistor that is connected at three terminals, shown as points A, B and C.
- Contact C is a sliding contact. Since resistance is proportional to length ($R \propto l$) for a fixed cross-sectional area, the position of C determines the ratio of resistance of AC to BC.
- When C is moved towards B, the resistance across AC (R_{AC}) becomes larger, and that across BC (R_{BC}) becomes smaller.
- $V_{out} = \left(\dfrac{R_{AC}}{R_{AC} + R_{BC}}\right) \times V_E$ where ($R_{AC} + R_{BC}$) is the total resistance of the resistor R, or

  $V_{out} = \left(\dfrac{AC}{AC + BC}\right) \times V_E$ where (AC + BC) is the length of the resistor R.

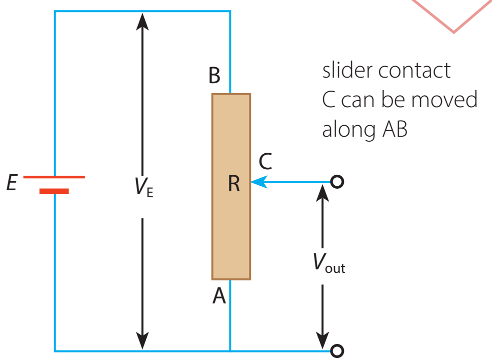


Figure 17.26 *A potentiometer used as a variable potential divider*

Figure 17.27 *A potentiometer is used in a dimmer switch to control the amount of light.*

Worked Example 17F

Figure 17.28 shows a 6 V cell connected to a potentiometer with a maximum resistance of 100 Ω. Calculate the output voltage V_{out} when the sliding contact is at

(a) A; **(b)** the midpoint between AB; **(c)** B.

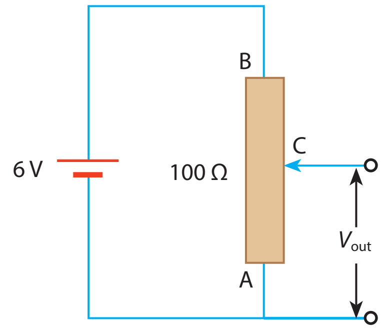


Figure 17.28

Solution

(a) When the contact is at A, the resistance across AC is zero.

Hence, the output voltage $V_{out} = 0$ V.

(b) When the contact is midway between AB, $R_{AC} = 50\ \Omega$ and $R_{BC} = 50\ \Omega$.

Hence, the output voltage is

$$V_{out} = \left(\frac{R_{AC}}{R_{AC} + R_{BC}}\right) \times V_E = \left(\frac{50}{50 + 50}\right)\Omega \times 6\text{ V} = 3\ \Omega$$

(c) When the contact is at B, $R_{AC} = 100\ \Omega$ and $R_{BC} = 0\ \Omega$.

Hence, output voltage V_{out} = input voltage = 6 V.

What components can be present in a variable potential divider?

Input transducers are electronic devices that respond to changes in physical conditions, such as temperature and light. They can be used in potential dividers to vary the output voltage. This enables electronic systems to respond to changes in the physical conditions.

Input transducers are widely used in control systems, electrical instruments and electronic communications. Examples include thermistors, LDRs, microphones, photocells, thermocouples and pressure sensors.

In this section, we will learn how the thermistor and the light-dependent resistor (LDR) (Figure 17.29) work. These transducers work in potential dividers to control the output voltage according to changes in physical conditions.

ENRICHMENT ACTIVITY

Find out about other environment-sensitive resistors. Discuss with your class how these resistors work. One example could be a pressure-sensitive resistor.

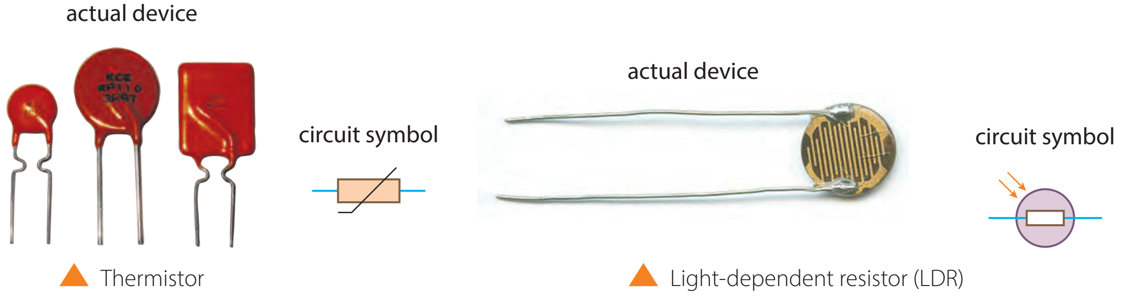


Figure 17.29 Thermistors and LDRs are examples of input transducers

LINK

Recall that the resistance of a metallic conductor increases with temperature which you have learnt in Chapter 16.

NTC thermistors, however, behave in the opposite manner.

Thermistors

A **thermistor** is a resistor whose resistance varies with temperature. An NTC thermistor has resistance that decreases as its temperature increases. The sensitivity of the thermistor to temperature allows it to be used in the circuits of appliances that measure or control temperature.

Figure 17.30 shows the use of an NTC thermistor R_{TH} in a potential divider.

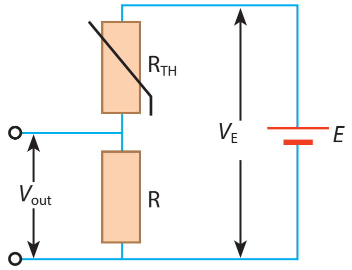
The output voltage is given by

$$V_{out} = \left(\frac{R}{R + R_{TH}}\right) \times V_E$$

where R_{TH} = resistance of the thermistor (in Ω);

R = resistance of the fixed resistor (in Ω);

V_E = voltage supplied by electrical source (in V).



The resistance R_{TH} of the NTC thermistor decreases as its temperature increases. Hence, the output voltage V_{out} also increases with temperature.

Figure 17.30 *NTC thermistor in a potential divider*

By using a voltmeter to measure V_{out}, we can derive the temperature. The output voltage V_{out} can also be used for other purposes, such as controlling switches that turn temperature alarms on or off.

QUICK CHECK

Thermistors are sensitive to visible light.

True or false?

Light-dependent resistors (LDRs)

A **light-dependent resistor (LDR)** has a resistance that decreases as the amount of light shining on it increases, and vice versa. Figure 17.31 in Worked Example 17G shows the effect of an LDR in a potential divider.

Worked Example 17G

Figure 17.31 shows an LDR, R_{LDR}, in a potential divider with a fixed resistor R of resistance 10 kΩ. The cell has an e.m.f. of 9 V. The resistance R_{LDR} of the LDR in two rooms, A and B, is given in Table 17.7

Table 17.7

Room	Resistance of LDR, R_{LDR} / kΩ
A	100
B	5

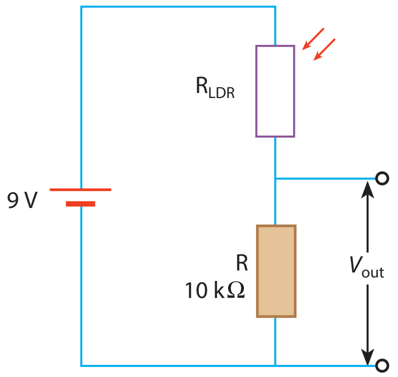


Figure 17.31

(a) One of the rooms had its lights switched off when the resistance of the LDR was measured. Based on your understanding of LDRs, which room was it? Why?

(b) Calculate the output voltage V_{out} across the fixed resistor R when the LDR is placed in rooms A and B.

Solution

(a) Room A; the resistance of an LDR increases when the amount of light shining on it decreases. Since the LDR has a higher resistance in room A, it is likely to be the room with its lights switched off.

(b) The output voltage V_{out} across resistor R is given by $V_{out} = \left(\frac{R}{R + R_{LDR}}\right) \times V$

In room A, $R_{LDR} = 100$ kΩ. Then $V_{out} = \left(\frac{R}{R + R_{LDR}}\right) \times V = \left(\frac{10}{10 + 100}\right)$ kΩ × 9 V = 0.82 V

In room B, $R_{LDR} = 5$ kΩ. Then $V_{out} = \left(\frac{R}{R + R_{LDR}}\right) \times V = \left(\frac{10}{10 + 5}\right)$ kΩ × 9 V = 6.0 V

Worked Example 17G shows how the output voltage of a potential divider varies with the amount of light shining on the LDR. When the light intensity increases, the resistance R_{LDR} decreases. This results in a higher V_{out}. The sensitivity of the LDR to light intensity allows it to be used in devices that measure light intensity (e.g. light meters) and in automatic streetlights (Figure 17.32).

Figure 17.32 *LDRs are used in streetlights. This enables the streetlights to automatically switch on when it is dark.*

Let's Practise 17.4

1. S Figure 17.33 shows a potential divider with a thermistor and a fixed resistor R of resistance 100 Ω connected to a 6 V cell. The resistance R_{TH} of the thermistor is 500 Ω at 0°C and 50 Ω at 100°C. Calculate the voltmeter readings at these two temperatures.
2. **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

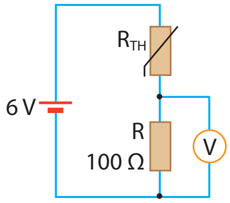


Figure 17.33

LINK TWB

Exercise 17C, pp. XX–XX

17.5 Electrical Safety

In this section, you will learn the following:

- State the hazards of damaged insulation, overheating cables, damp conditions and excess current from overloading of plugs, extension leads, single and multiple sockets when using a mains supply.
- Know that a mains circuit consists of a live wire (line wire), a neutral wire and an earth wire.
- Explain why a switch must be connected to the live wire for the circuit to be switched off safely.
- Explain the use and operation of trip switches and fuses, and choose appropriate fuse ratings and trip switch settings.
- Explain why the outer casing of an electrical appliance must be either non-conducting (double-insulated) or earthed.
- State that a fuse without an earth wire protects the circuit and the cabling for a double-insulated appliance.

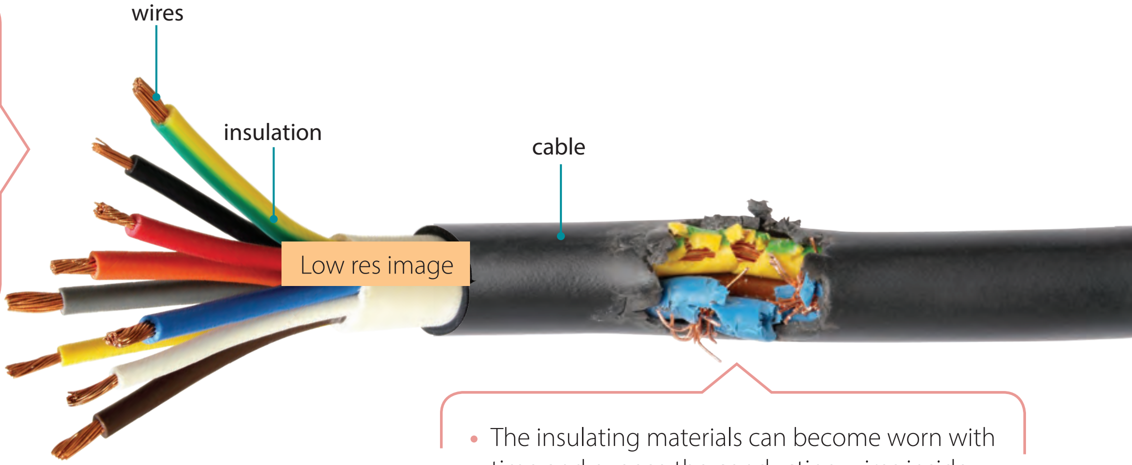
Electrical hazards

Electrical faults in appliances or circuits can cause fires and electric shocks. Electricity can be a hazard when electrical insulation is damaged, cables are overheated, or conditions are damp.

Damaged insulation

Figure 17.34 describes how damaged insulation can be dangerous.

- Wires that carry electricity from the voltage supply to electrical appliances are wound together to form cables.
- These cables are enclosed by insulating materials such as PVC or rubber.



- The insulating materials can become worn with time and expose the conducting wires inside.
- The exposed conducting wires can cause electric shocks if touched.

Figure 17.34 *Damaged insulation on an electrical cable*

Overheating of cables

Overheated cables can cause fires. Two common causes of overheated cables are listed below:

1 **Overloaded power sockets**
When a power socket is overloaded with many appliances, an unusually large current flows through the wires (Figure 17.35).

2 **Use of inappropriate wires**
The resistance of a conducting wire is inversely proportional to its cross-sectional area. This means that a thin wire has a higher resistance and generates more heat, compared to a thick wire. Therefore, when appliances are being wired, manufacturers must make sure that the wires are of appropriate thickness. Generally, thin wires are used for appliances that need less power, such as lamps, while thick wires are used for appliances that need more power, such as kettles.

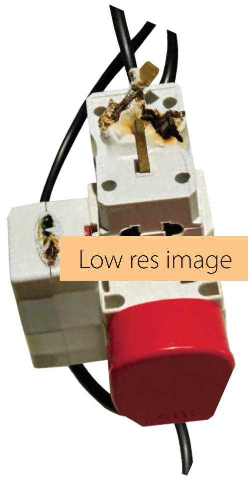


Figure 17.35 *Overloading a power socket can damage plugs and appliances.*

LINK

Recall this relationship between resistance and cross-sectional area which you have learnt in Chapter 16.

Damp conditions

Many electrical accidents occur in damp conditions. For example, a hair dryer on a wet sink (Figure 17.36) can cause electric shocks if the conducting wires are exposed or have damaged insulation.

Water in contact with the uninsulated electrical wires provides a conducting path for current. As the human body can only withstand an alternating current of about 50 mA, a large current will cause burns, uncoordinated contraction of the heart muscles, or even death. Therefore, electrical appliances should be kept in dry places and handled with dry hands.

Figure 17.36 *A hair dryer connected to a socket is left on a wet sink. This can be very dangerous.*

What does a typical mains circuit in the home look like?

Various safety features are installed in the circuits in our homes. Figure 17.37 shows a circuit in the home.

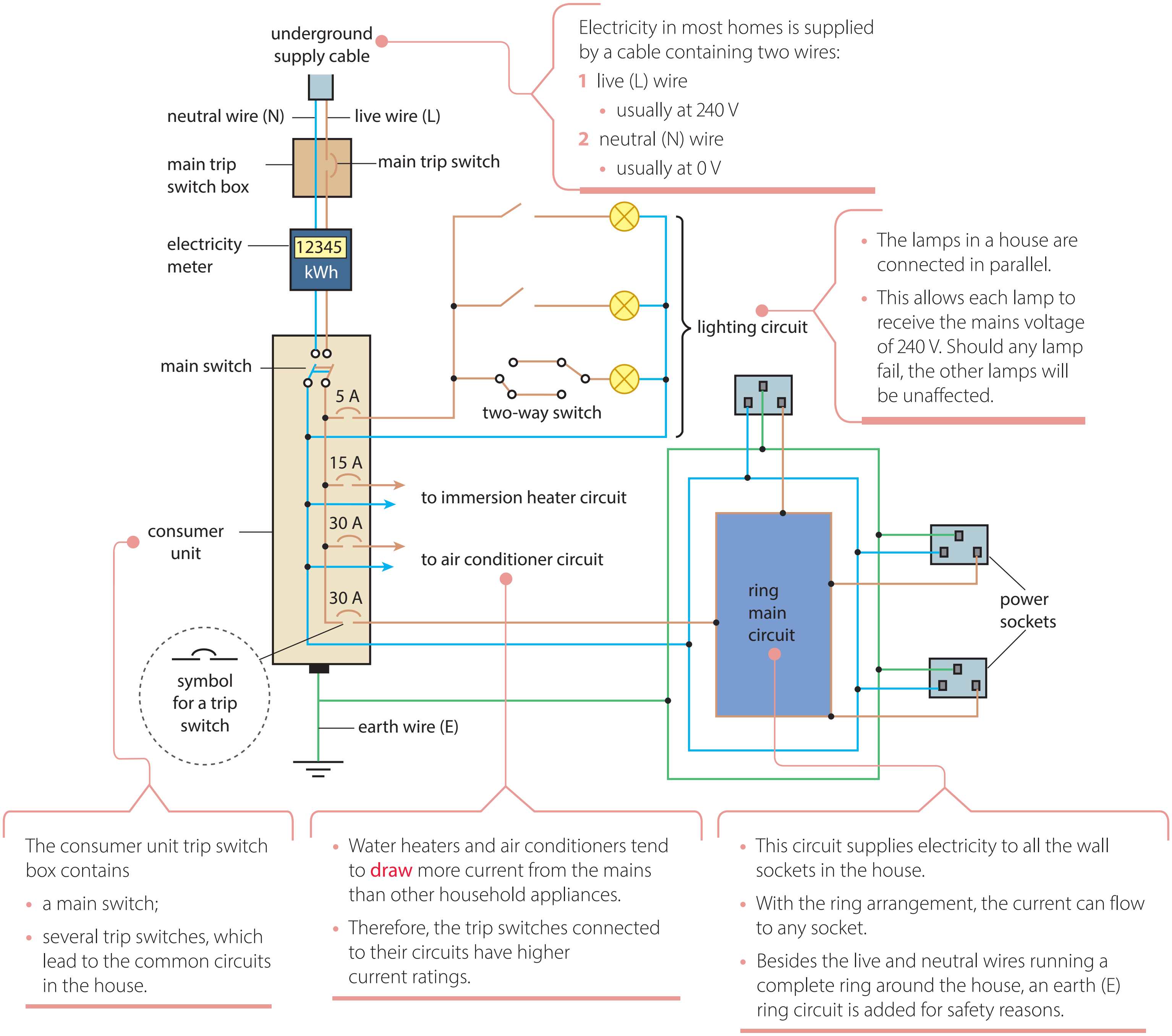


Figure 17.37 *Typical home circuitry*

WORD ALERT A-Z

Draw: use

HELPFUL NOTES

Trip switches are also known as *circuit breakers*.

What features in the mains circuit keep us safe in the event of a fault?

Safety features that can be found in our homes are listed below:

1 Trip switches	**2** Fuses
3 Switches	**4** Earthing
5 Three pin plugs	**6** Double insulation

Trip switches

Trip switches are safety devices that can switch off the electrical supply in a circuit when large currents flow through them. Without trip switches, a surge of current can damage home appliances or even start a fire.

Figure 17.38 shows the trip switches in a consumer unit. The trip switches are labelled with various cut-off currents, such as 10 A and 16 A. Trip switches are connected to live wires. Should there be a current surge due to a fault, the trip switches will **trip** and cut off the current to the appliances. This ensures that the appliances are isolated from the mains, and the users do not get electric shocks.

WORD ALERT

Trip: shut down

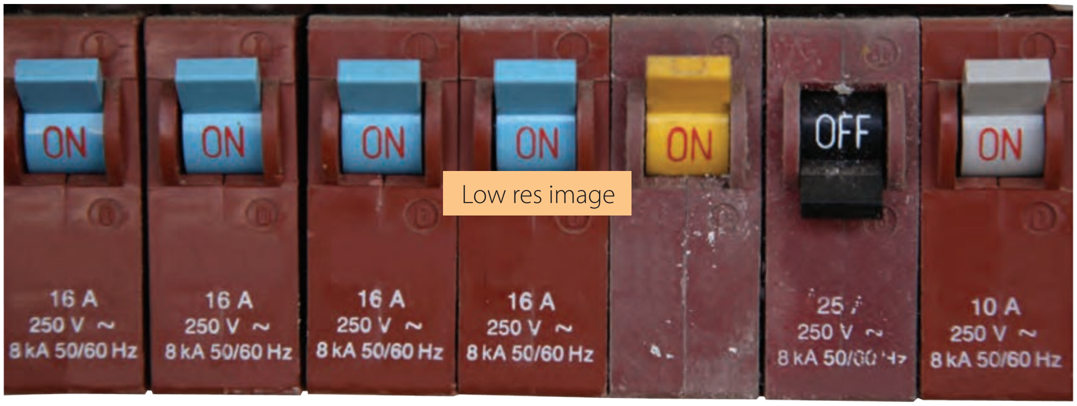


Figure 17.38 Trip switches in a consumer unit

Trip switches can be reset by switching them on again. This should be done only after the fault in the circuit has been corrected.

Fuses

A **fuse** is a safety device added to an electrical circuit to prevent excessive current flow. It has the same function as a trip switch. However, a fuse must be replaced after it blows, whereas a trip switch can be reset after it trips.

A fuse consists of a short piece of wire (Figure 17.39). The wire is made thin so that when a large current flows through it, it heats up and melts. When a fuse blows, a gap is created in the circuit. The circuit is opened, and current stops flowing through the circuit.

PHYSICS WATCH

Scan this page to watch a clip of an experiment to study the working principle of a fuse.

All fuses have a rated value. This value indicates the maximum current that can flow through a fuse before it blows. In general, fuses with thicker wires can conduct larger currents before blowing, and therefore have higher rated values. Typical household fuses are rated at 1 A, 2 A, 3 A, 5 A, 10 A and 13 A.

For safety reasons, the following points should be considered when selecting and installing fuses:

- The fuse of an electrical appliance should have a rated value that is slightly higher than the appliance the electrical appliance draws under normal operating conditions.
- The fuse should be connected to the live wire. This is done so that the current to the appliance will be cut off immediately after a large current melts the fuse wire inside the cartridge. The appliance will not be at a potential of 240 V.
- The mains power supply must be switched off before replacing a fuse.

Figure 17.39 A cartridge fuse contains a thin metal wire, which melts when a large current flows through it.

QUICK CHECK

If a fuse blows, it is safe to just replace the fuse and carry on using the device.

True or false?

HELPFUL NOTES

Water heaters draw more current than most appliances and therefore consume more power. Save electricity by only using water heater on cold days.

Worked Example 17H

A hot water heater is rated at 2880 W, 240 V. Calculate the operating current, and suggest a suitable rating for a fuse to protect the heater from overheating.

Figure 17.40 *Water heater*

Solution

Given: Power P of heater = 2880 W

Voltage V = 240 V

Let I = operating current.

Using $P = VI$, $I = \frac{P}{V} = \frac{2880\text{ W}}{240\text{ V}} = 12\text{ A}$

A suitable fuse will have a fuse rating that is slightly higher than the operating current of the water heater. Thus, a 13 A fuse will be suitable.

Worked Example 17I

The following appliances are operating in a kitchen circuit:

- 50 W fruit blender
- 800 W microwave oven
- 400 W refrigerator
- 1.5 kW electric kettle

Electricity is supplied to the kitchen at 240 V. The kitchen circuit is protected by a trip switch with a rating of 20 A.

(a) What is the current flowing through the trip switch when all the appliances are operating at the same time?

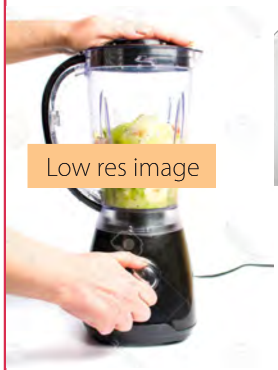
(b) Does the trip switch trip?

Solution

(a) Since all the appliances are operating at the same time, the total power P = 50 W + 400 W + 800 W + 1500 W = 2750 W

Using $P = VI$, $I = \frac{P}{V} = \frac{2750\text{ W}}{240\text{ V}} = 11.5\text{ A}$

(b) As the current is lower than the rating of the trip switch, the trip switch does not trip, and all the appliances can operate safely.



Switches

Switches are designed to break or complete an electrical circuit. They should be fitted to the live wire of the appliance.

For example, if an electrical fault causes the metal casing of an appliance to be at high voltage, a switch on the live wire can disconnect the voltage supplied to the metal casing. Figures 17.42 and 17.42 show how a switch fitted to the neutral wire does not prevent electric shocks, while a switch fitted to the live wire does.

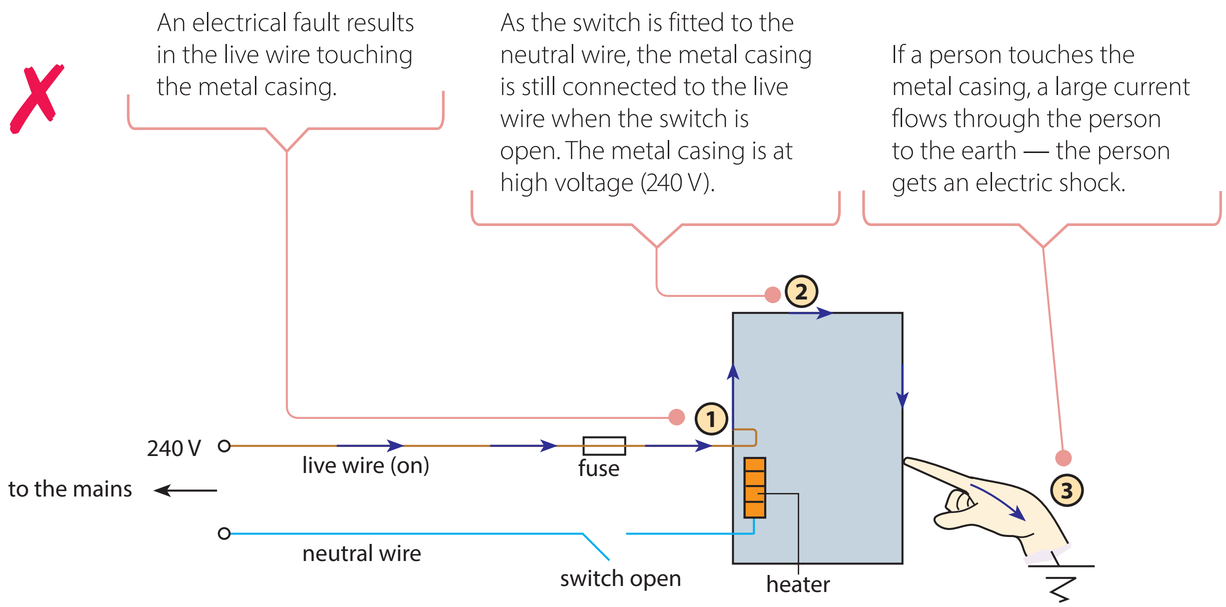


Figure 17.42 *Incorrect position for a switch — the switch should not be fitted to the neutral wire*

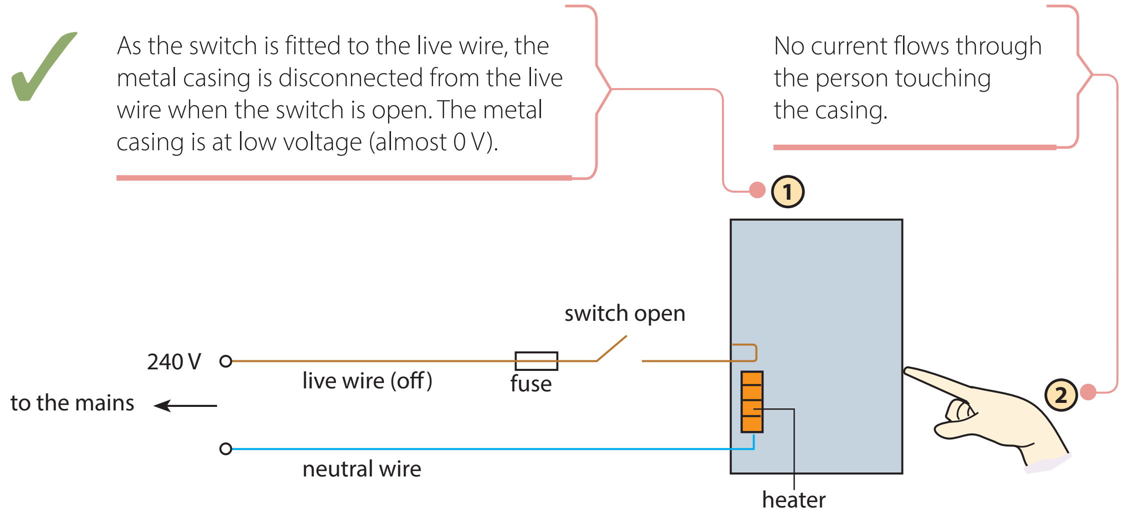


Figure 17.43 *Correct position for a switch — the switch should be fitted to the live wire*

Earthing

There are usually three wires in a home circuit — the live (L) wire, the neutral (N) wire and the earth (E) wire (Figure 17.44).

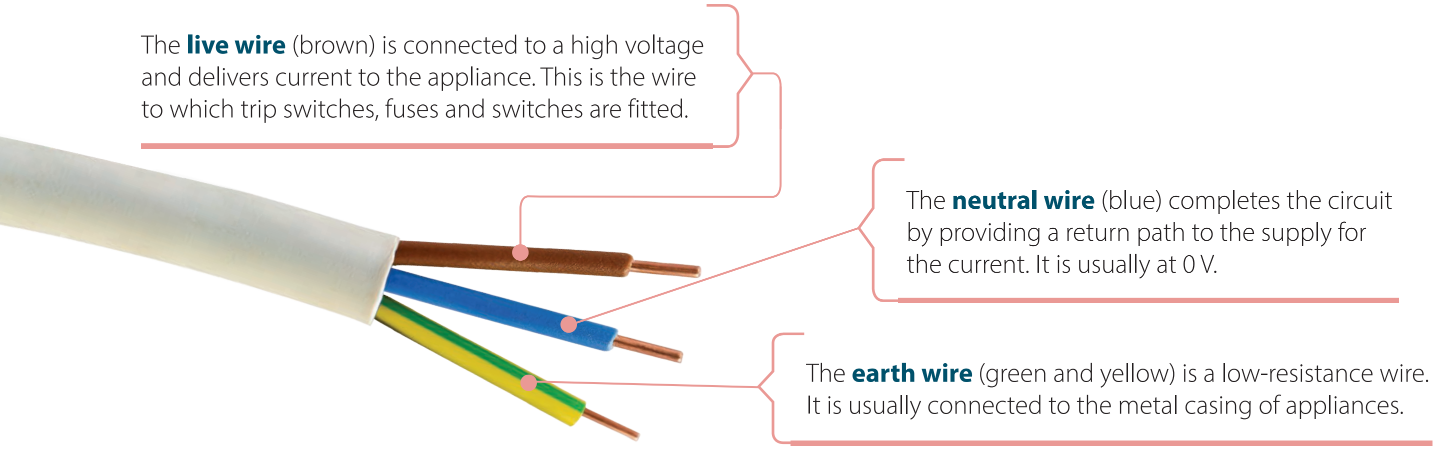


Figure 17.44 *The three wires in a home circuit*

Figures 17.45 and 17.46 show how earthing prevents electric shocks when an electrical fault is present.

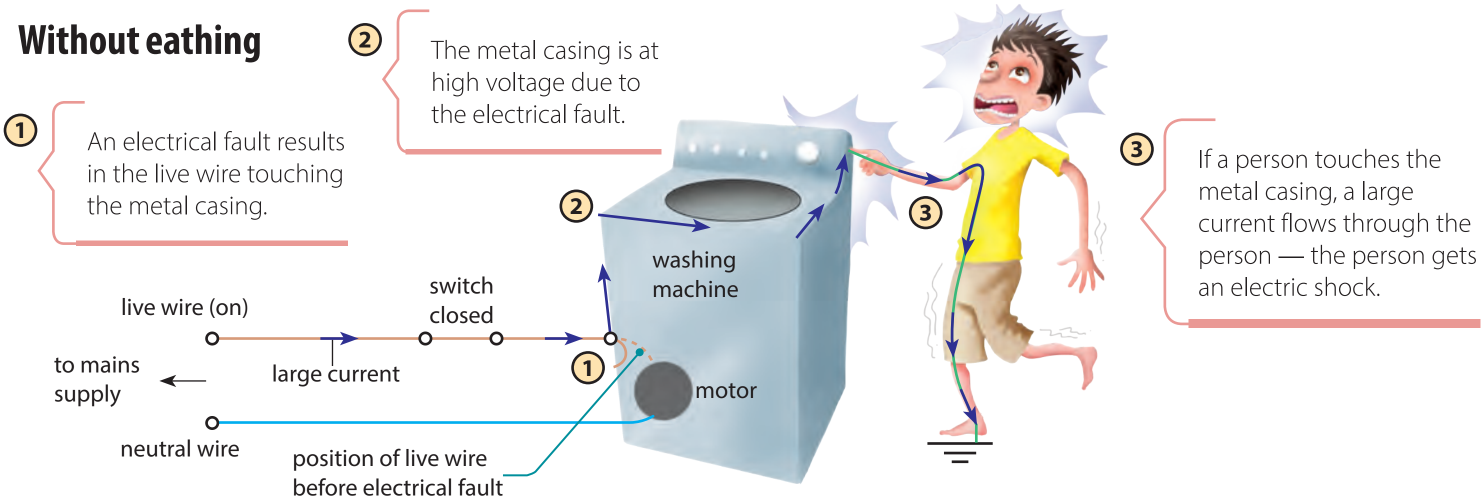


Figure 17.45 *The absence of earthing can cause electric shocks.*

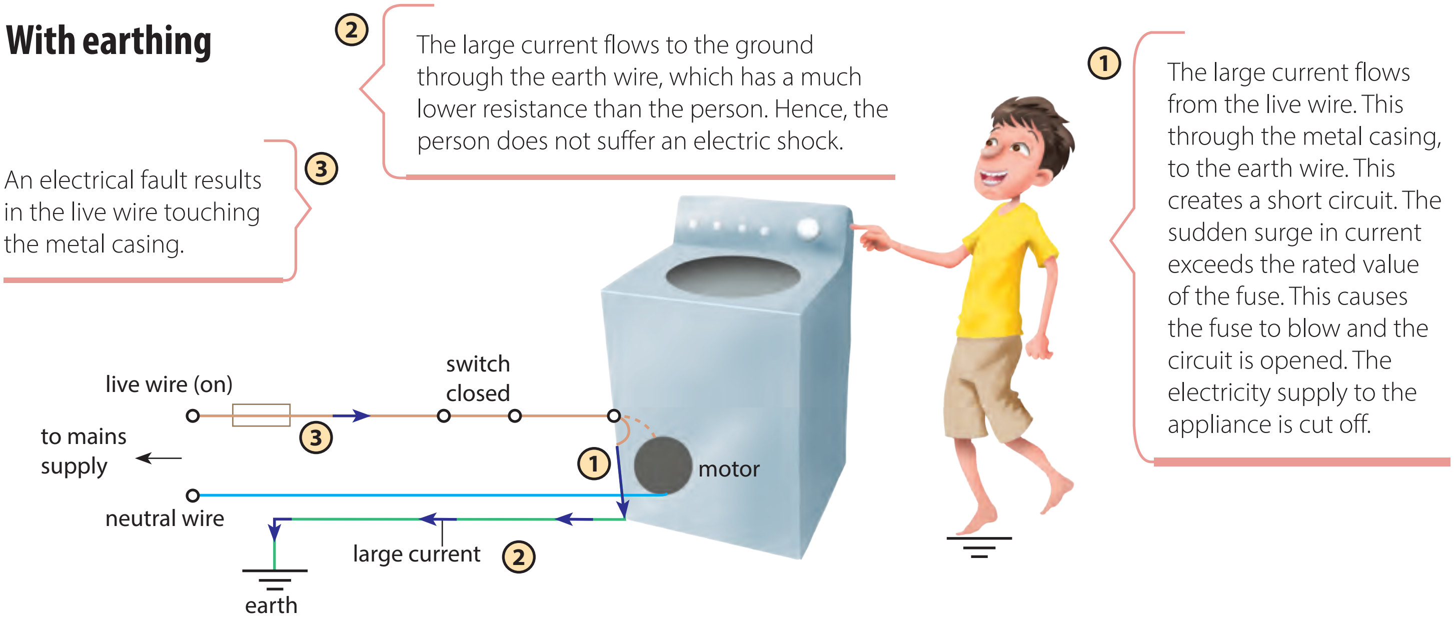


Figure 17.46 *Earthing prevents electric shocks.*

Three-pin plugs

A fused plug connects an electrical appliance to the mains supply via the power socket. The fused plug commonly used in some countries is the **three-pin plug** (Figures 17.47).

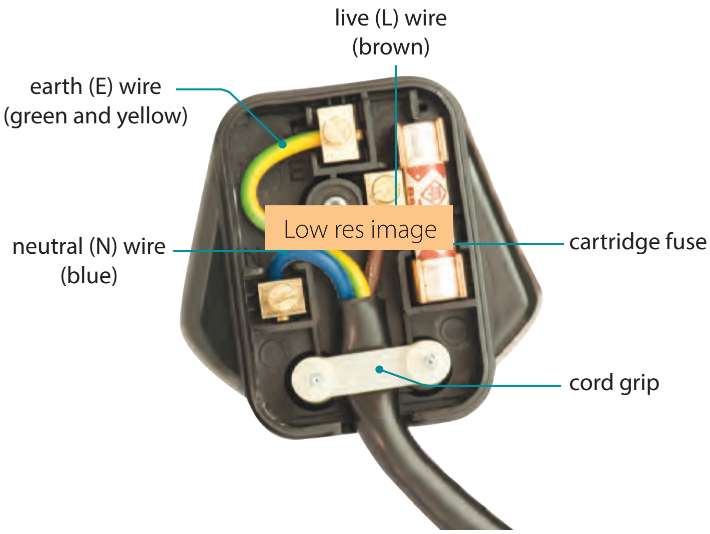


Figure 17.47 *Inside parts of a three-pin plug*

The fused plug is also known as a safety plug. The cartridge fuse inside the plug protects the appliance when there is an electrical fault. If excessive current flows in the appliance, the fuse blows. This breaks the circuit and isolates the appliance with the fault so that overheating does not damage it.

Double insulation

Some household appliances use two-pin plugs instead of three-pin plugs. For such appliances, there is no earth wire. These appliances use double insulation to protect users from electric shocks. Figure 17.48 shows such an appliance and the double insulation symbol.

Double insulation is a safety feature that can replace the earth wire. Appliances that have double insulation usually use a two-pin plug. This is because only the live and neutral wires are required.

Double insulation provides two levels of insulation:

1 The electric cables are insulated from the internal components of the appliance.

2 The internal components are insulated from the external casing.

Appliances with double insulation typically have non-metallic casings, such as plastic.

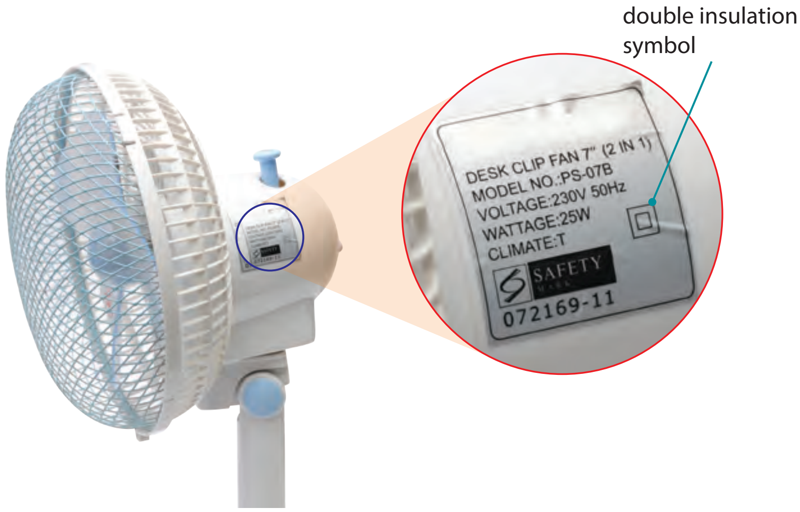


Figure 17.48 *Double-insulated appliances carry the double insulation symbol.*

Let's Practise 17.5

1 State **three** safety precautions that someone operating electrical devices should take to avoid an electric shock

2 State the function of the following safety features, and how they should be connected in a circuit:

(a) Trip switch **(b)** Fuse **(c)** Earth wire

3 Explain why do some appliances use a three-pin plug, while others use a two-pin plug?

4 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

TWB **LINK**

Exercise 17D–17E, pp. XX–XX

Exercise 17F Let's Reflect, p. X

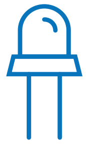
Let's Map It

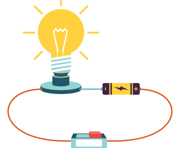
ELECTRICAL CIRCUITS

can be represented by → **Circuit diagrams**

includes → **Circuit components**

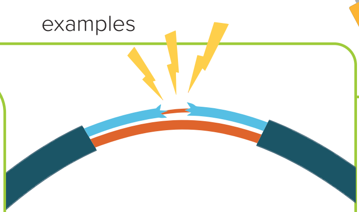
examples → Cells, batteries, power supplies, generators, potential dividers, switches, resistors (fixed and variable), heaters, NTC thermistors, light-dependent resistors (LDRs), lamps, motors, ammeters, voltmeters, magnetising coils, transformers, fuses and relays, S diodes, S light-emitting diodes (LEDs)





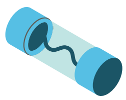
can cause ↓

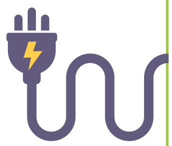
Electrical hazards
- Damaged insulation
- Overheating cables
- Damp conditions
- Excess current from overloading



can be avoided by using

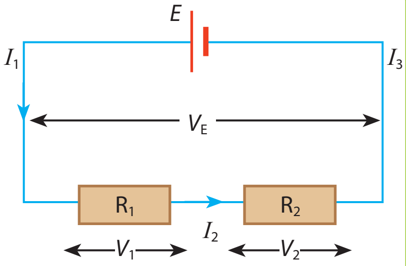
Safety features
- Trip switches
- Fuses
- Switches
- Earthing
- Three-pin plugs
- Double insulation





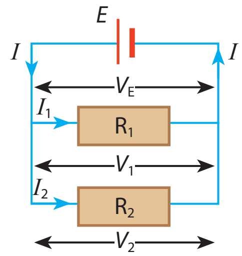
examples

Series circuits



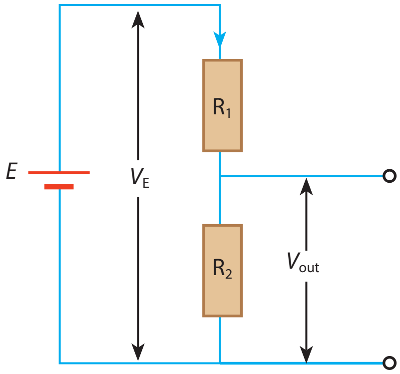
- Current: $I_1 = I_2 = I_3$
- Potential difference: $V_E = V_1 + V_2$
- Combined resistance: $R = R_1 + R_2$

Parallel circuits

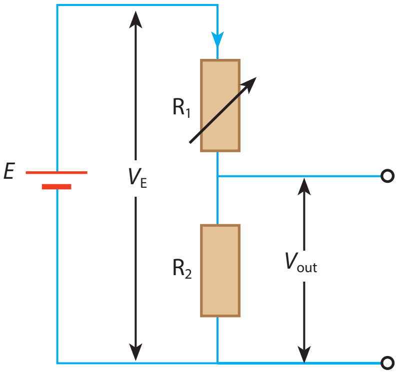


- Current: $I = I_1 + I_2$
- Potential difference: $V_E = V_1 = V_2$
- S Combined resistance: $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$

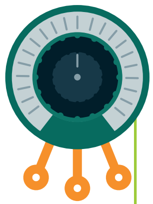
Potential divider circuit with fixed resistors
- Fixed R_1 and fixed R_2

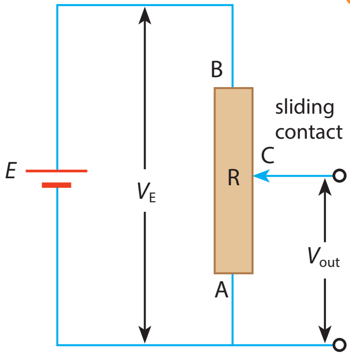


Variable potential divider circuit with rheostat
- Variable R_1 and fixed R_2



Variable potential divider circuit with potentiometer
- Variable R_1 and variable R_2





S $V_{out} = \frac{R_2}{R_1 + R_2} \times V_E$

S In general: $\frac{R_1}{R_2} = \frac{V_1}{V_2}$

S $V_{out} = \frac{R_{AC}}{R_{AB}} \times V_E$

Let's Review

Section A: Multiple-choice Questions

1 Figure 17.49 shows three identical resistors.

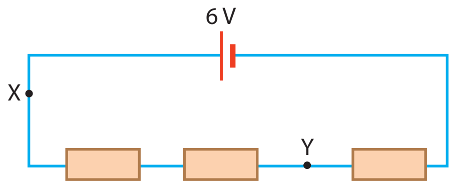


Figure 17.49

What is the voltage reading of a voltmeter connected across XY?

A 2 V **B** 3 V
C 4 V **D** 6 V

2 In Figure 17.50, the reading on ammeter A_2 is 1 A and that on ammeter A_4 is 3 A. What are the readings on ammeters A_1 and A_3?

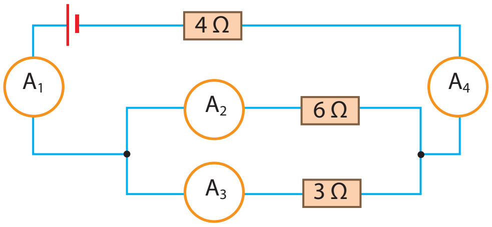


Figure 17.50

	A_1 reading/A	A_3 reading/A
A	1.5	0.5
B	2	1
C	3	1
D	3	2

3 Ⓢ In Figure 17.51, resistor R_1 is connected to an e.m.f. source. The ammeter reading is 2 A and the voltmeter reading is 6 V. In Figure 17.52, a new resistor R_2 is now connected in parallel with resistor R_1. The ammeter and voltmeter readings are now 3 A and 6 V respectively.

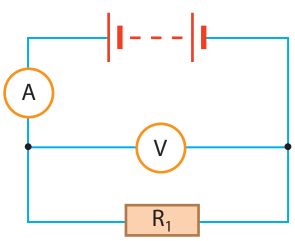


Figure 17.51

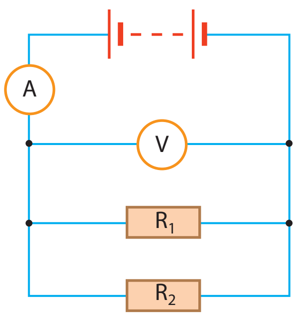


Figure 17.52

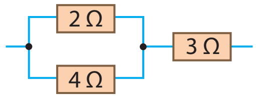
What is the resistance of resistor R_2?

A 2 Ω **B** 3 Ω
C 6 Ω **D** 9 Ω

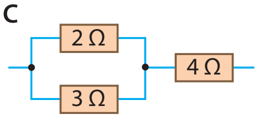
4 Ⓢ Which of the following combinations of resistors has the lowest resistance?

A

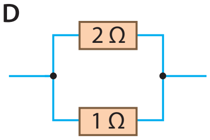
B



C



D



5 An appliance has a current of 7 A. Which fuse should be used to protect the appliance in the event of a fault?

A 1 A **B** 3 A
C 5 A **D** 13 A

6 Which safety precaution reduces the risk of an electrical fire if a device becomes faulty?

A Earth wire **B** Trip switch
C Insulation **D** Plug

For questions 7 and 8, refer to Figure 17.53. In the circuit shown, the resistors have equal resistance *R*.

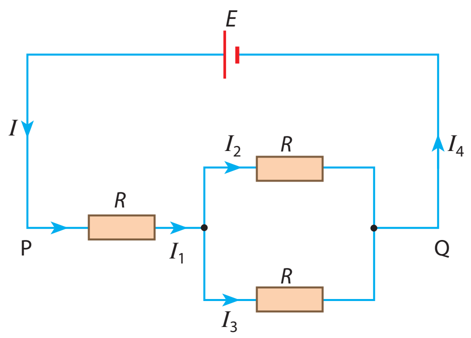


Figure 17.53

7 Ⓢ The combined resistance between PQ is

A $\frac{1}{3}R$. **B** $\frac{3}{2}R$.
C $2R$. **D** $3R$.

8 What can be deduced about I, I_1, I_2, I_3 and I_4?

A $I = I_1 = I_4 = I_2 + I_3$
B $I = I_1 = I_2 = I_3 + I_4$
C $I > I_1 > I_4$ and $I_2 = I_1$
D $I > I_1 > I_4$ and $I_4 = I_2 + I_3$

Let's Review

9 Ⓢ In the potential divider in Figure 17.54, the variable resistor R_1 has a maximum resistance of 4 Ω. What are the minimum and maximum possible values of V_{out}?

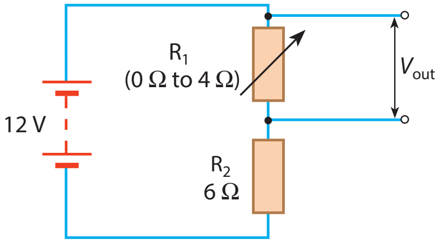


Figure 17.54

	Minimum V_{out}/V	Maximum V_{out}/V
A	0	4.8
B	0	6
C	2	4.8
D	6	12

10 Ⓢ The circuit in Figure 17.55 is used to detect the level of sunlight. The resistance of the LDR is 1 MΩ in the dark and 100 Ω in bright sunlight. What is the voltmeter reading in dark and bright conditions?

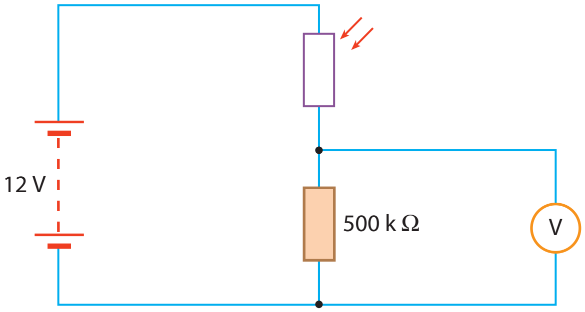


Figure 17.55

	Voltmeter reading in the dark/V	Voltmeter reading in bright sunlight/V
A	4	0
B	4	12
C	8	0
D	8	4

11 Figure 17.56 shows a thermistor connected in a potential divider circuit at room temperature. The resistance of this thermistor decreases with an increase in its temperature. Which of the following happens to the voltmeter reading when the thermistor is heated?

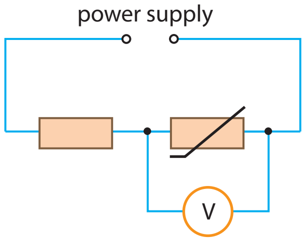


Figure 17.56

A Decreases
B Decreases and then increases
C Increases
D Stays the same

Section B: Short-answer and Structured Questions

1 Ⓢ For the circuit in Figure 17.57, calculate the
(a) combined resistance across AB;
(b) combined resistance across CD;
(c) combined resistance of the whole circuit;
(d) current flowing through the 6 Ω resistor.

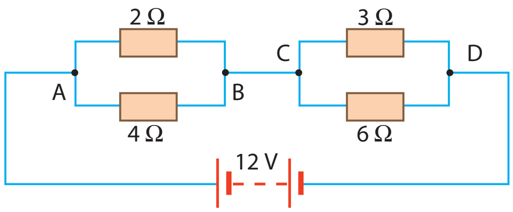


Figure 17.57

2 A 6 V cell is connected to three resistors in the circuit shown in Figure 17.58. The current flowing through the source is 0.8 A. Calculate the
(a) current I_1;
(b) current I_2;
(c) value of the resistance of resistor R.

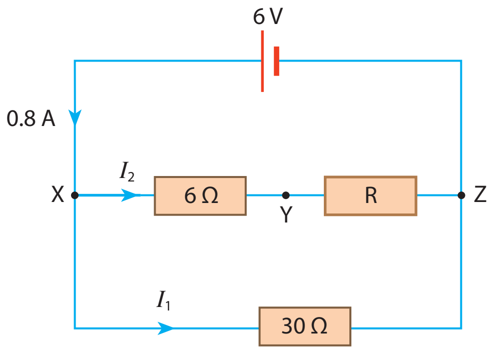


Figure 17.58

3 **(a)** Using four identical resistors, design a circuit in which the p.d. across

(i) each resistor is one-fourth of the e.m.f.;

(ii) each resistor is the same as the e.m.f.;

(iii) each resistor is half of the e.m.f.;

(iv) one resistor is the same as the e.m.f., and the p.d. across each of the other three resistors is less than the e.m.f.

(b) Compare the advantages and disadvantages of connecting lamps in series and in parallel. Explain your answer.

4 The electrical wiring in a house is complex. When an electrical failure occurs, it is hard to determine the cause of the failure. To determine the cause, an electrician uses a voltmeter to determine the p.d. across two points in a circuit. Table 17.8 shows the readings the electrician took for the circuit shown in Figure 17.59.

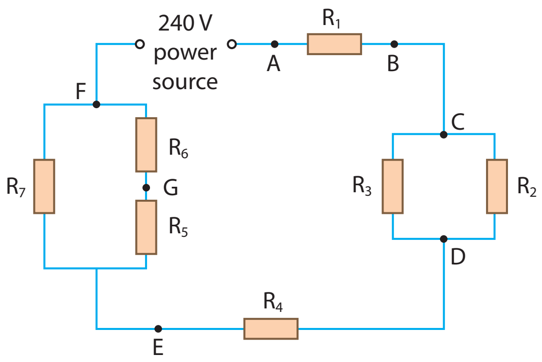


Figure 17.59

Table 17.8

Points	P.d. across the points
A and B	40 V
B and C	0 V
C and D	0 V
D and E	100 V
E and F	50 V
E and G	30 V
G and F	20 V

(a) Explain why there is no p.d. across BC.

(b) If the current flowing through R_4 is 0.50 A, determine the resistances of

(i) R_4; **(ii)** R_1.

(c) State the location of the fault in the circuit, and suggest a possible cause of the fault.

(d) If the current flowing through R_4 is 0.50 A, and the current flowing through R_7 is one-fourth of that flowing through R_5 and R_6, calculate the resistances of

(i) R_7; **(ii)** R_5; **(iii)** R_6.

(e) Calculate the combined resistance across EF.

5 S Variable resistors are used in circuits to produce variable output voltages.

(a) Using an e.m.f. of 9 V, a variable resistor with a range of 0 Ω to 12 Ω, and a fixed resistor of 24 Ω, design a circuit that can produce a variable output voltage of 0 V to 3 V.

(b) Perform calculations to show that your design produces the desired voltage output.

6 Figure 17.60 shows a circuit in which lamps 1 and 2 (of resistances R_1 and R_2) are connected in series. Figure 17.61 shows the same circuit after lamps 1 and 2 are replaced by a single lamp 3 of equivalent resistance R.

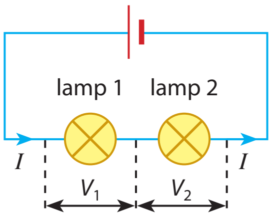


Figure 17.60

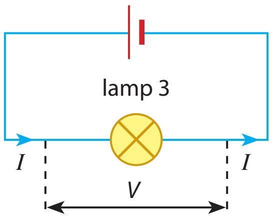


Figure 17.61

According to the principle of conservation of energy,

power dissipated by lamp 3	=	power dissipated by lamp 1	+	power dissipated by lamp 2

(a) Given that power P dissipated by a lamp is $P = IV$,
where I = current flowing through the lamp,
V = p.d. across the lamp,
use the principle of conservation of energy to derive the formula for the combined resistance R of lamps 1 and 2.

(b) Using a similar method as in **(a)**, derive the formula for the combined resistance of lamps 1 and 2 when they are arranged in parallel.

CHAPTER

18 Electromagnetic Effects

PHYSICS WATCH

Scan this page to watch a clip about the uses of electromagnetic effects.

QUESTIONS

- Look at the photo. What is the drone used for?
- What does d.c. stand for?
- Which parts of the drones make use of d.c. motors?
- Why do the motors have permanent magnets?

Farms in the rural areas of Japan are facing a problem. They are left in the hands of aging farmers who may no longer have the strength to do the work. Many of the young people prefer to find jobs in the city. This aging of the agricultural industry is also happening in countries such as Thailand.

One answer to the problem is to use drones. Drones are unmanned aerial vehicles that can operate using small d.c. motors. The motors have permanent magnets that are made of alloys. These magnets need to be small and light so that the motors can provide enough thrust for a lift off.

Perhaps, using drone technology in agriculture could lure the young people back to the rural farms.

18.1 Electromagnetic Induction

In this section, you will learn the following:
- Know that a conductor moving across a magnetic field or a changing magnetic field linking with a conductor can induce an e.m.f. in the conductor.
- Describe an experiment to demonstrate electromagnetic induction.
- State the factors affecting the magnitude of an induced e.m.f.
- S Know that the direction of an induced e.m.f. opposes the change causing it.
- S State and use the relative directions of force, field and induced current.

In chapter 15, you have learnt that a current flowing through a conductor produces a magnetic field around it. In 1831, an English scientist named Michael Faraday discovered that the converse is true — a changing magnetic field produces an induced current. This effect is known as *electromagnetic induction*.

Electromagnetic induction is the process through which an induced e.m.f. is produced in a conductor due to a *changing magnetic field*.

LINK

Recall the magnetic field pattern around a current-carrying conductor.

Refer to Chapter 15.

What did Faraday discover?

Figure 18.1 shows the apparatus that Faraday used to test whether a moving magnet could induce a current.

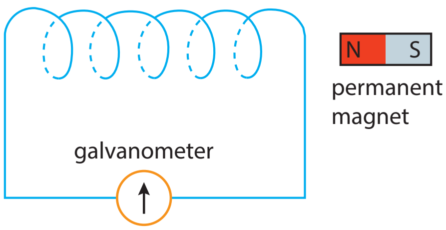


Figure 18.1 *Faraday's solenoid experimentremains constant.*

These were Faraday's observations:
- When a magnet was inserted into a solenoid, the galvanometer needle was deflected in one direction.
- When the magnet was withdrawn from the solenoid, the galvanometer needle was deflected in the other direction.
- When the magnet was stationary in the solenoid, the galvanometer needle was not deflected.

From his observations, Faraday concluded that a relative movement between the solenoid and the magnet induced an electromotive force (e.m.f.) in the circuit. The induced e.m.f. drove an induced current which was then detected by the galvanometer.

Faraday also found that the magnitude of this induced e.m.f. could be increased by increasing the

1 number of turns in the solenoid;

2 strength of the magnet;

3 speed at which the magnet moves with respect to the solenoid.

WORD ALERT

Deflected: caused to move

Flux: the rate of flow of something across an area; magnetic flux is a measure of the quantity of magnetic field surrounding a magnetic object.

The laws of electromagnetic induction

There are two laws of electromagnetic induction.

Faraday's Law of electromagnetic induction states that the magnitude of the induced e.m.f. in a circuit is directly proportional to the rate of change of magnetic flux in the circuit.

S **Lenz's Law** states that the direction of the induced e.m.f., and hence the induced current in a closed circuit, is always such that its magnetic effect opposes the motion or change producing it.

We can carry out Let's Investigate 18A to demonstrate the laws of electromagnetic induction.

PHYSICS WATCH

Scan this page to explore a simulation on electromagnetic induction.

Let's Investigate 18A

Objective
To demonstrate the laws of electromagnetic induction

Apparatus
Bar magnet, solenoid of wire, connecting wires, centre-zero galvanometer or other sensitive ammeter

Procedure

1. Connect the ends of a solenoid to a sensitive centre-zero galvanometer with connecting wires.
2. Move the S pole of a permanent bar magnet into the solenoid, and note any deflection on the galvanometer (Figure 18.2).
3. Once the bar magnet is inside the solenoid, hold it stationary and note any deflection on the galvanometer.
4. Next, move the S pole of the magnet out of the solenoid, and note any deflection on the galvanometer.
5. Repeat steps 2 to 4, using the N pole of the same bar magnet.

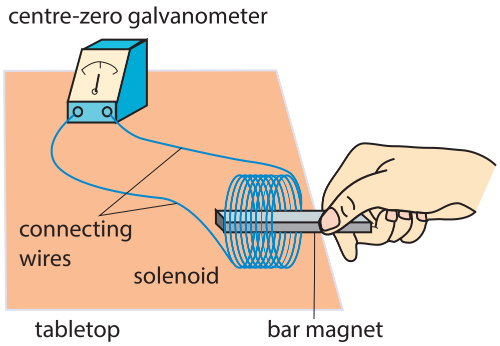


Figure 18.2

LINK PWB
Practical 18A, pp. XX–XX

Observation and discussion
Tables 18.1 and 18.2 summarise the observations and discussion of this investigation.

Table 18.1 *S pole of bar magnet moved into and out of the solenoid*

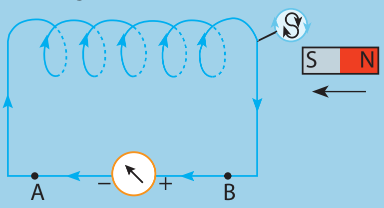
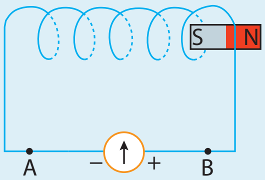
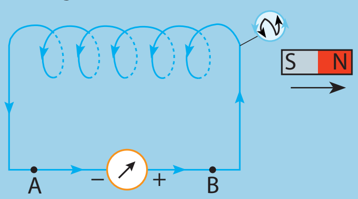
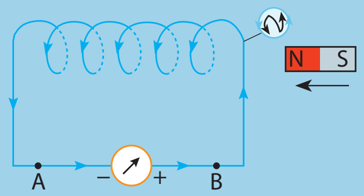
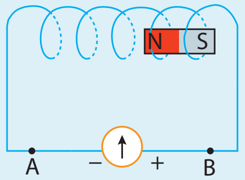
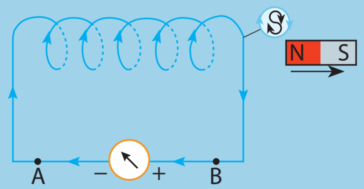
Observation	Discussion
(a) S pole of magnet moved towards the solenoid  The galvanometer needle was deflected momentarily to one side.	• When the S pole of the bar magnet was moved towards the solenoid, the galvanometer needle was deflected momentarily to one side. • This shows that an e.m.f. was induced in the coil and a current flowed through the galvanometer. • The induced current produced an S pole at the end of the solenoid to repel the S pole of the bar magnet moving towards it.
(b) S pole of magnet held stationary in the solenoid  The galvanometer needle was not deflected.	• No current was induced in the circuit.
(c) S pole of magnet drawn out of the solenoid  The galvanometer needle was deflected momentarily to the other side.	• When the S pole of the bar magnet was moved away from the solenoid, the galvanometer needle was deflected momentarily to the other side. • This shows that an e.m.f. was induced in the coil and a current flowed through the galvanometer. • The induced current produced an N pole at the end of the solenoid to attract the S pole of the barmagnet moving away from it.

Table 18.2 *N pole of bar magnet moved into and out of the solenoid*

Observation	Discussion
(a) N pole of magnet moved towards the solenoid  The galvanometer needle was deflected momentarily to one side.	• When the N pole of the bar magnet was moved towards the solenoid, the galvanometer needle was deflected momentarily to one side. • This shows that an e.m.f. was induced in the coil and a current flowed through the galvanometer. • The induced current produced an N pole at the end of the solenoid to repel the N pole of the bar magnet moving towards it.
(b) N pole of magnet held stationary in the solenoid  The galvanometer needle was not deflected.	• No current was induced in the circuit.
(c) N pole of magnet drawn out of the solenoid  The galvanometer needle was deflected momentarily to the other side.	• When the N pole of the bar magnet was moved away from the solenoid, the galvanometer needle was deflected momentarily to the other side. • This shows that an e.m.f. was induced in the coil and a current flowed through the galvanometer. • The induced current produced an S pole at the end of the solenoid to attract the N pole of the bar magnet moving away from it.

Worked Example 18A

In Figure 18.4, a short bar magnet passes through a long solenoid. A galvanometer is connected across the solenoid.

(a) Sketch a graph of the galvanometer needle deflection θ against time t, starting from the instant shown in Figure 18.4 to the time the magnet emerges from the solenoid.

(b) Using the principles of electromagnetic induction, explain the shape of the graph you sketched in **(a)**.

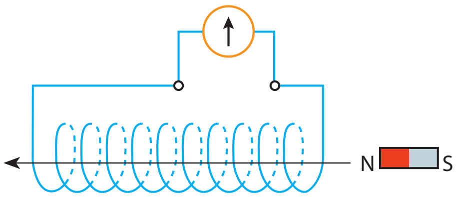


Figure 18.4

ENRICHMENT INFO

Conservation of Energy and Lenz's Law

There is a link between the conservation of energy we have seen in other chapters and Lenz's Law. This is used in electromagnetic braking.

A current is induced in a spinning aluminium disc because of the presence of a magnetic field. The induced current produces a force on the disc. This force will either accelerate or decelerate the disc, depending on the direction of the current. In one direction the disc would continue to accelerate and would never slow down — impossible. Hence, the current must be in the direction predicted by Fleming's right-hand rule (see page 335).

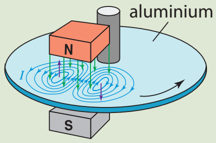


Figure 18.3

Solution

(a) Figure 18.5 shows the graph of galvanometer needle deflection θ against time t.

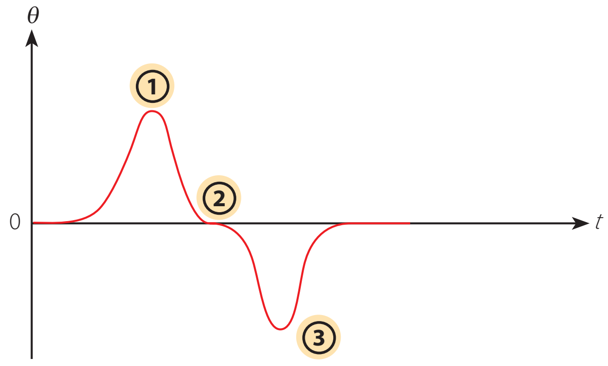


Figure 18.5

(b) At 1:

- At the instant when the bar magnet travels past the midlength point of the solenoid, there is no change in the magnetic flux in the solenoid.
- There is no induced e.m.f., and hence no induced current to cause the galvanometer needle to be deflected.

At 2:

- As the N pole of the bar magnet enters the solenoid, there is a change in the number of magnetic field lines linking the solenoid (i.e. magnetic flux in the solenoid changes).
- By Faraday's Law, the change of the magnetic flux in the solenoid results in an induced e.m.f. in the circuit. This e.m.f. drives an induced current through the closed circuit. The induced current produces a galvanometer needle deflection θ.
- By Lenz's Law, the induced current creates an N pole at the right end of the solenoid to oppose the incoming N pole. Thus, the galvanometer needle is deflected momentarily to one side.

At 3:

- As the S pole of the bar magnet exits the solenoid, there is again a change in the magnetic flux in the solenoid.
- By Faraday's Law, this produces an induced e.m.f. and hence an induced current.
- By Lenz's Law, the induced current creates an N pole at the left end of the solenoid to oppose the outgoing S pole. Thus, the galvanometer needle is deflected momentarily to the other side.

Let's Practise 18.1

1 A bar magnet is pushed towards one end of a solenoid, as shown in Figure 18.6.

(a) Explain what happens to the galvanometer needle.

(b) Describe how you would increase the angle of deflection of the galvanometer needle.

(c) S Explain which pole is induced at end A of the solenoid.

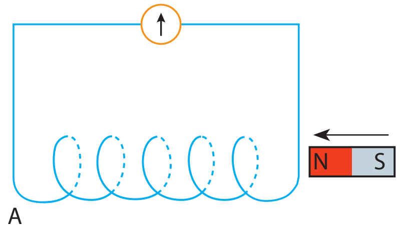


Figure 18.6

2 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

Exercise 18A, pp. XX–XX

18.2 The A.c. Generator

In this section, you will learn the following:

- Describe a simple form of a.c. generator and the use of slip rings and brushes.
- Sketch and interpret graphs of e.m.f. against time for simple a.c. generators and relate the position of the generator coil to the peaks, troughs and zeros of the e.m.f.

HELPFUL NOTES

An e.m.f. is induced in a conductor only when there is a change in magnetic flux. If the conductor is at rest in a constant magnetic field or moving in the same direction as the magnetic field lines are pointing, no e.m.f. is induced.

One important use of electromagnetic induction is in the generation of electricity. The **alternating current (a.c.) generator** uses alternating current to transform mechanical energy into electrical energy.

How can we generate a.c. from motion?

Figure 18.7 shows how a simple a.c. generator works. Note that the direction of the induced current flowing in the coil can be found using **Fleming's right-hand rule**.

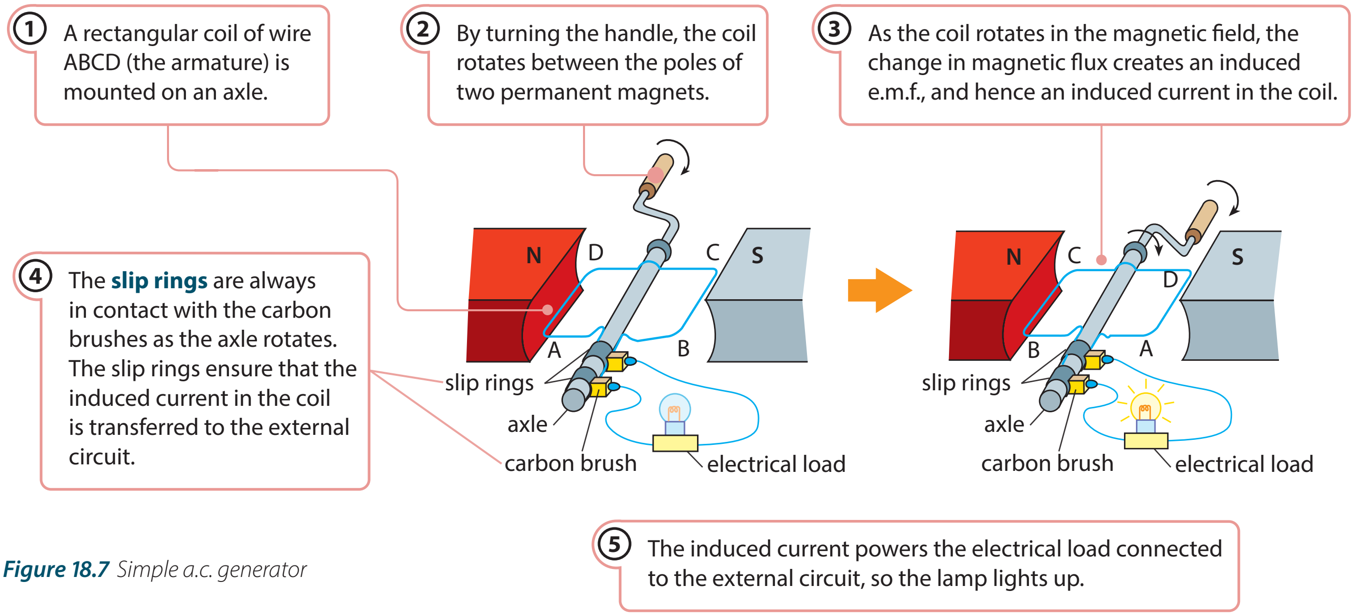


Figure 18.7 Simple a.c. generator

Fleming's right-hand rule

The British physicist John Ambrose Fleming came out with a simple hand rule to find the direction of induced current when a conductor moves in a magnetic field (Figure 18.8).

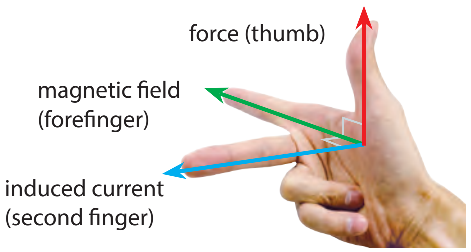


Figure 18.8 Fleming's right-hand rule

① Point your thumb, forefinger and second finger at right angles to one another using your right hand.

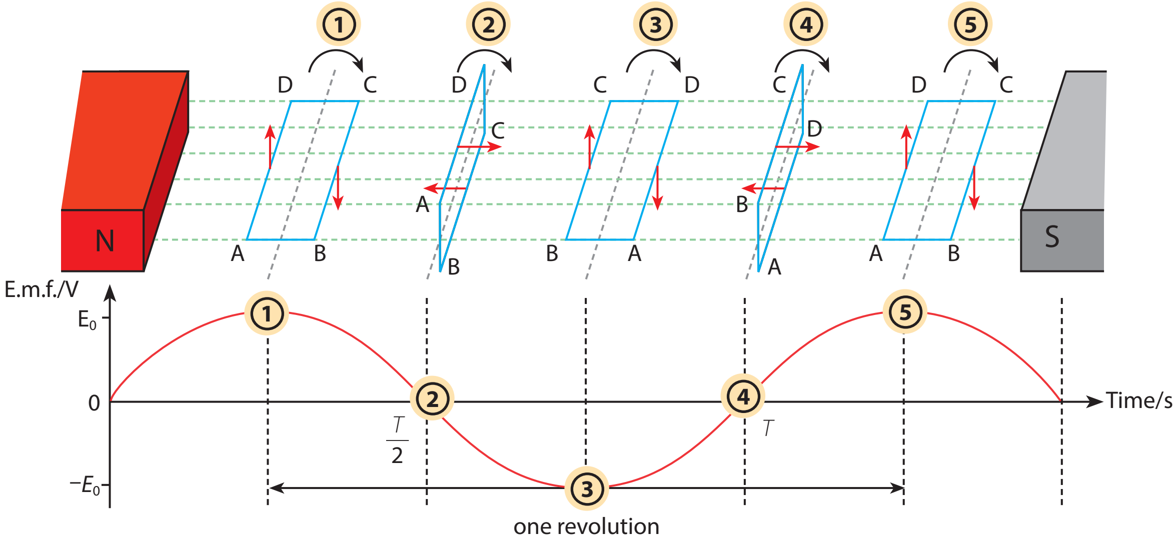
② Point your forefinger in the direction of the magnetic field (N-to-S direction) and your second finger in the direction of the induced current.

③ Your thumb then gives the direction of the motion of the wire, i.e., the direction of the force. In fact, given any two of the directions, we can deduce the remaining one.

What does the voltage-time graph look like for an a.c. generator?

At different positions, the rate at which the coil cuts across the magnetic field differs. Figure 18.9 shows how the magnitude of the output voltage (induced e.m.f.) changes as the coil rotates. Note that the alternating voltage in turn produces an alternating current (hence the name *alternating current* generator).

The horizontal and vertical red arrows in the diagram shows the direction of the forces produced. These forces cause the coil to turn.



① When the plane of the coil is parallel to the magnetic field, the arms AD and BC cut across the magnetic field lines at the greatest rate. Since the rate of change of magnetic flux is maximum, the magnitude of the induced e.m.f. is maximum.

② When the plane of the coil is perpendicular to the magnetic field, the arms AD and BC do not cut across the magnetic field lines. Since the rate of change of the magnetic flux is zero, the magnitude of the induced e.m.f. is zero.

③ After the coil rotates half a cycle, it is parallel to the magnetic field again. The magnitude of the induced e.m.f. is maximum. Note that since the arms AD and CB are moving in directions opposite to those in step 1, the direction of the induced e.m.f. is opposite to that in step 1.

④ The arms AD and BC of the coil do not cut across the magnetic field lines. The magnitude of the induced e.m.f. is zero.

⑤ The coil has rotated one complete cycle. It is parallel to the magnetic field again, and hence the maximum induced e.m.f. is produced.

Figure 18.9 *The induced e.m.f. varies with the position of the coil.*

We can increase the magnitude of the induced e.m.f. of an a.c. generator by

1. increasing the number of turns in the coil (Figure 18.10);
2. using stronger permanent magnets;
3. increasing the frequency of rotation of the coil (Figure 18.11);
4. winding the coil around a soft iron core to strengthen the magnetic flux linking the coil.

QUICK CHECK

Look at the coil in step 1 of Figure 18.9. The induced current is flowing from D to A.

True or false?

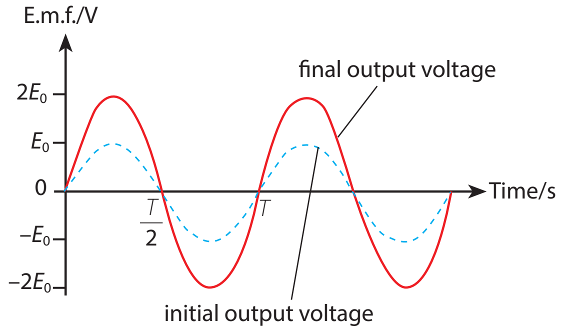


***Figure 18.10** Doubling the number of turns of the coil doubles the maximum output voltage*

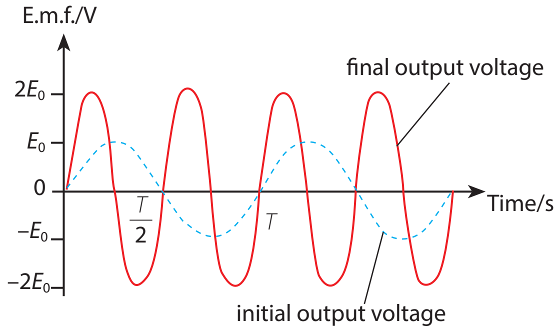


***Figure 18.11** Doubling the frequency f doubles the maximum output voltage.*

Worked Example 18B

(a) Explain why rotating a coil between two magnets generates an induced e.m.f.

(b) On the same axes, sketch the graphs of induced e.m.f. against time for a time interval of 0.6 s for the coil when it rotates

- 5.0 times per second, and the induced e.m.f. generated has a maximum value of 40 mV;
- 2.5 times per second. Note that the maximum value of the e.m.f. changes when the frequency of rotation changes.

  Assume that the plane of the coil is parallel to the magnetic field at t = 0 s.

Solution

(a) When the coil rotates, it cuts across the magnetic field lines, and there is a change in the magnetic flux in the coil. By Faraday's Law, this change induces an e.m.f. in the coil.

(b) Period $T_1 = \frac{1}{f_1} = \frac{1}{5.0\text{ Hz}} = 0.2\text{ s}$

Period $T_2 = \frac{1}{f_2} = \frac{1}{2.5\text{ Hz}} = 0.4\text{ s}$

The maximum value of the induced e.m.f. (i.e. the amplitude of the graph) is halved when the frequency of rotation is halved (Figure 18.12).

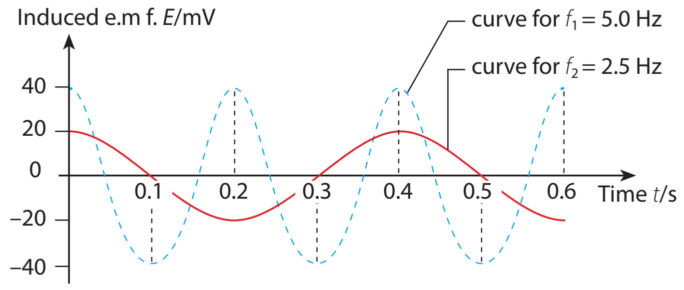


Figure 18.12

HELPFUL NOTES

1 Hz means 1 cycle per second.

$$\text{So } \frac{1}{5.0\text{ Hz}} = \frac{1}{5.0\,\frac{1}{s}} = 0.2\text{ s}$$

The practical design of an a.c. generator

In a simple a.c. generator, it is the coil that rotates between fixed magnets. However, we can also have an a.c. generator in which magnets rotate with respect to fixed coils. This type of a.c. generator is called a **fixed coil generator**. An example of a fixed coil generator is the bicycle dynamo (Figure 18.13).

S

1. A magnet is attached to an axle and a wheel. As the wheel rotates, the magnet rotates too.
2. The magnetic field rotates with respect to a fixed coil. This changes the magnetic flux in the coil. An induced e.m.f. is generated, and this in turn creates an induced current.
3. The induced current is channelled directly to the external circuit through the output terminals. Slip rings and carbon brushes are not needed.

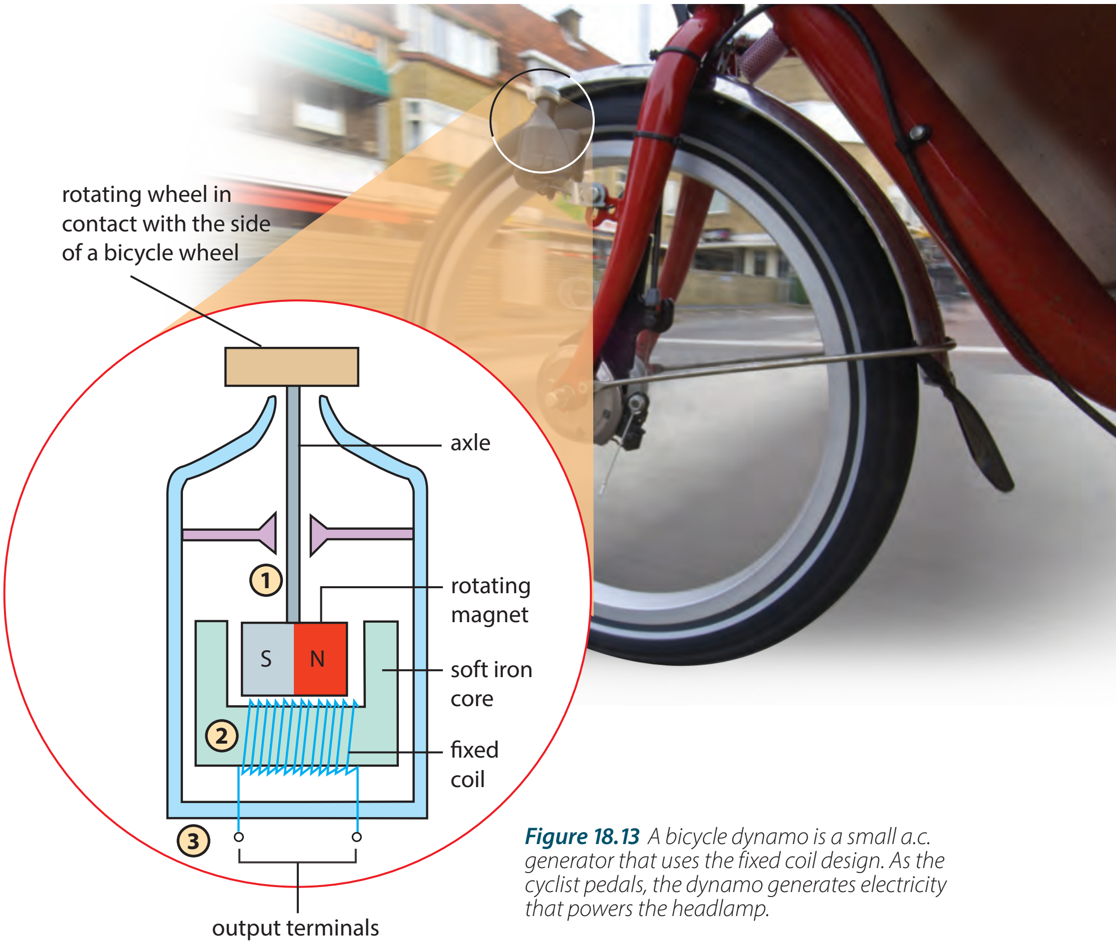


Figure 18.13 *A bicycle dynamo is a small a.c. generator that uses the fixed coil design. As the cyclist pedals, the dynamo generates electricity that powers the headlamp.*

In practical applications, a fixed coil a.c. generator is favoured for the following reasons:

1. It does not require carbon brushes, which wear out easily and need to be replaced frequently.
2. It is less likely to break down from overheating. This is because it does not use slip rings and carbon brushes. An eroded connection between slip rings and carbon brushes has increased resistance, which can generate large quantities of heat.
3. It is more compact.

Let's Practise 18.2

1. Name the components of an a.c. generator that allow the transfer of the induced alternating current to an external circuit.
2. Sketch a graph of output voltage against time of an a.c. generator for two complete rotations of the coil.
3. **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

Exercise 18B, pp. XX–XX

18.3 Magnetic Effect of a Current

In this section, you will learn the following:

- Describe the pattern and direction of the magnetic field due to currents in straight wires and in solenoids.
- Describe an experiment to identify the pattern of the magnetic field (including direction) due to currents in straight wires and in solenoids.
- Describe how the magnetic effect of a current is used in relays and loudspeakers and give examples of their application.
- S State the qualitative variation of the strength of the magnetic field around straight wires and solenoids.
- S Describe the effect on the magnetic field around straight wires and solenoids of changing the magnitude and direction of the current.

How did Oersted discover electromagnetism?

In 1820, Hans Christian Oersted, a Danish professor, discovered the magnetic effect of an electric current by accident. During a class demonstration, he noticed that when a current was flowing through a wire, it caused the needle of a compass nearby to be deflected. This indicated the presence of a magnetic field. Oersted's observation eventually led to the discovery of **electromagnetism** — the relationship between electricity and magnetism.

Figure 18.14 shows the result of Oersted's experiment. Note that wire XY was placed in the north–south direction. Oersted's experiment showed that a magnetic field was present when a current flowed through wire XY.

A current-carrying conductor produces a magnetic field around it.

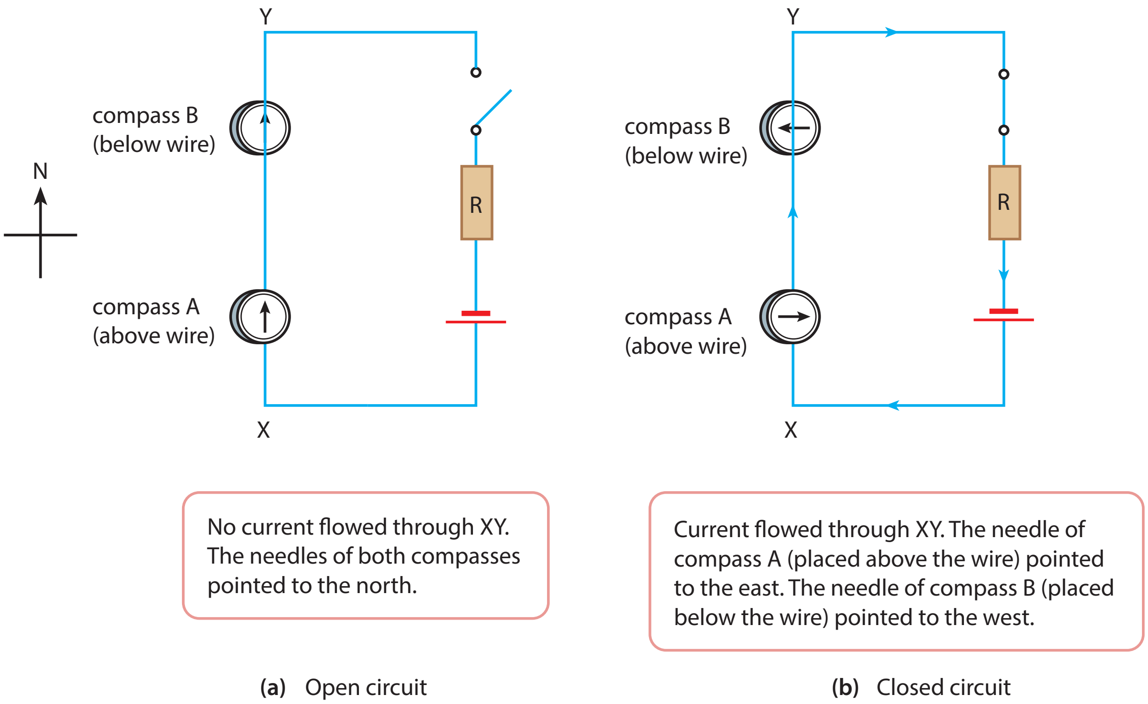


Figure 18.14 *The positions of the needles of compasses A and B in Oersted's experiment*

What are the shapes and directions of magnetic field lines?

Magnetic field pattern around a straight wire

Let's Investigate 18B describes an experiment that can be conducted to plot the magnetic field pattern around a straight current-carrying wire.

Let's Investigate 18B

Objective

To plot magnetic field lines around a straight current-carrying wire with a compass

Apparatus

Straight wire, plotting compass, cardboard, pencil, e.m.f. source

Procedure

1 Thread a wire through a small hole in a sheet of cardboard. The wire should be perpendicular to the cardboard sheet (Figure 18.15). Connect the wire to an e.m.f. source such that the current flows up the wire.

2 Place a compass on the cardboard sheet.

3 On the cardboard sheet, mark the positions of the S and N ends of the compass needle with pencil dots X and Y respectively.

4 Move the compass so that the S end of the needle is now at Y (Figure 18.16).

5 Mark the new position of the N end of the needle with a third dot Z.

6 Repeat steps 2 to 5, placing the compass at different distance from the wire until several field lines are drawn.

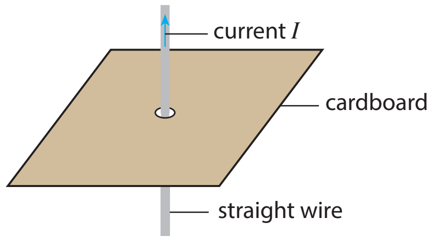


Figure 18.15 A wire threaded through a cardboard sheet

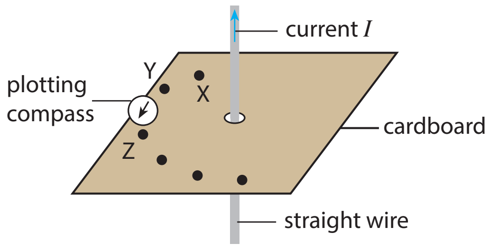


Figure 18.16 The positions of the S and N ends of the compass needle are marked with pencil dots.

Observation and discussion

- The magnetic field plot obtained consisted of concentric circles (Figure 18.17).
- The circles nearer the wire were closer to one another. This implies that the magnetic field was stronger at regions nearer the wire.

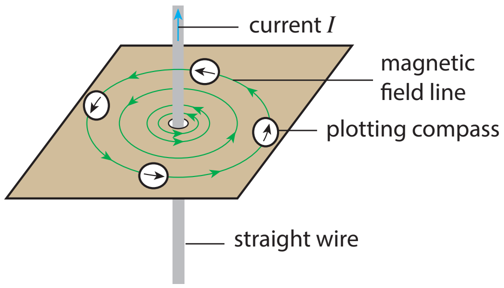


Figure 18.17 The magnetic field pattern of a straight wire

We can determine the direction of the magnetic field around the wire using the **right-hand grip rule** (Figure 18.18).

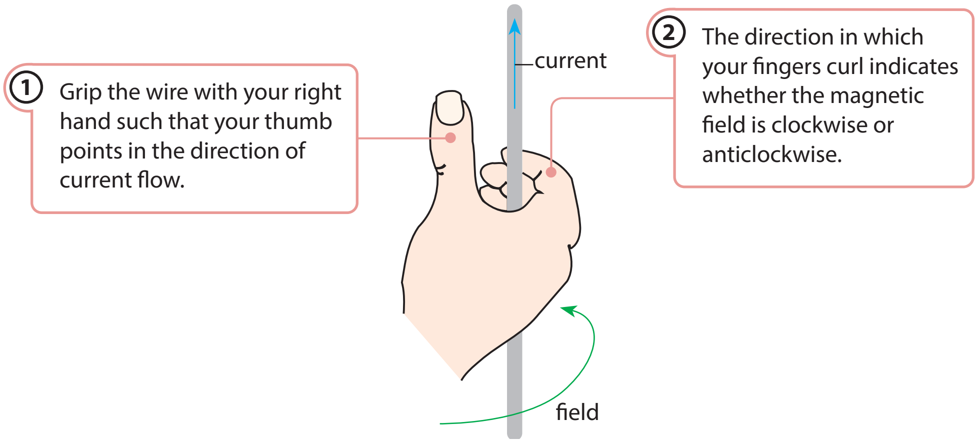


Figure 18.18 *The right-hand grip rule*

The factors that affect the direction and strength of a magnetic field around a current-carrying straight wire are shown in Figures 18.19 and 18.20.

(a) Direction of current reversed

The direction of the magnetic field of a current-carrying wire is reversed when the direction of the current is reversed.

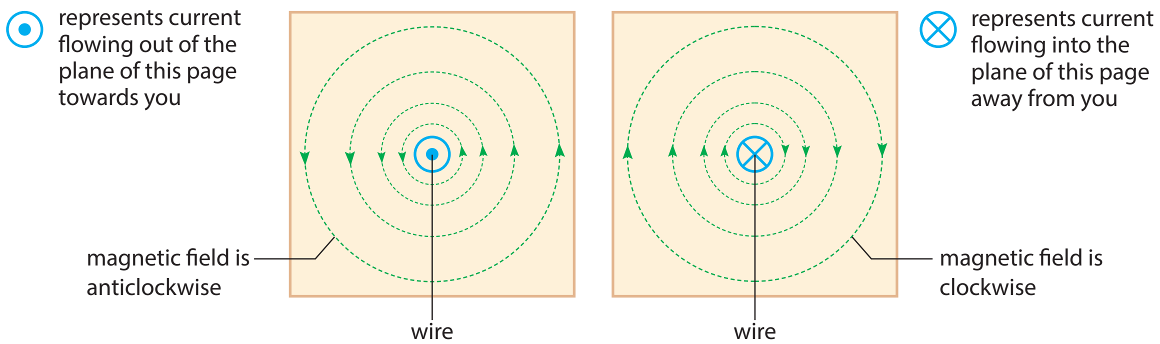


Figure 18.19 *When the direction of the current is reversed, the direction of the magnetic field is reversed.*

(b) Magnitude of current increased

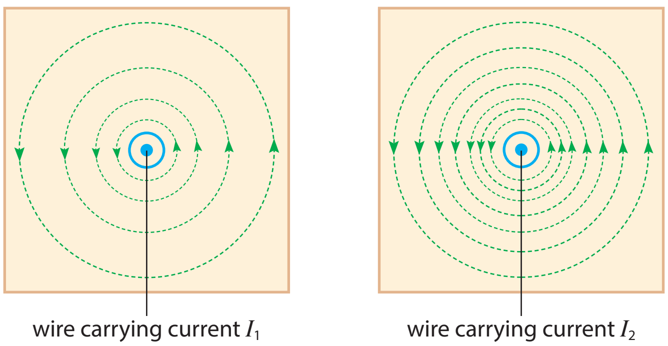


Figure 18.20 *When the current is increased from I_1 to I_2, the strength of the magnetic field increases.*

S *The strength of the magnetic field of a current-carrying wire increases when the current is increased.* Note that the strength of the magnetic field around the wire is not uniform. It depends on the distance from the wire. The magnetic field is stronger closer to the wire. This is represented by drawing the magnetic field lines closer together near the wire.

PHYSICS WATCH

Scan this page to explore a simulation on magnetic field patterns.

HELPFUL NOTES

When drawing the magnetic field around a straight current-carrying wire, remember that the magnetic field lines should be further apart with increasing distance from the wire.

Magnetic field pattern of a solenoid

We can do a similar experiment to the one in Let's Investigate 18B using a solenoid.

Figure 18.21 shows the magnetic field pattern of a solenoid.

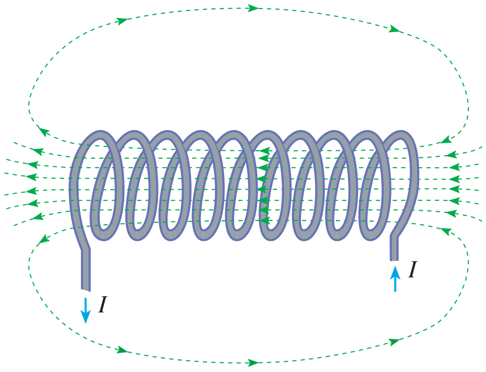


Figure 18.21 *Diagram of the magnetic field lines of a solenoid*

From the diagram, we observe the following:

- The magnetic field pattern of a solenoid resembles that of a bar magnet. Thus, the solenoid acts like a bar magnet. It has two poles and can be used as an electromagnet.
- The magnetic field lines inside the solenoid are closer together than the field lines outside. This means that the magnetic field inside the solenoid is stronger. The magnetic field inside the solenoid can be taken to be uniform.

In addition, if a soft iron core is placed within the solenoid, it will concentrate the magnetic field lines and increase the magnetic field strength of the solenoid.

The magnetic field strength in a solenoid can be increased by

- increasing the current flowing through the solenoid;
- increasing the number of turns per unit length of the solenoid;
- placing a soft iron core within the solenoid.

HELPFUL NOTES

You can use the right-hand grip rule (Figure 18.22) to deduce which end of a solenoid the north pole is.

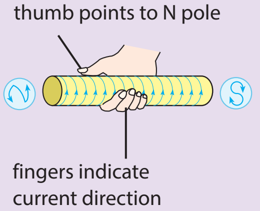


Figure 18.22

QUICK CHECK

The right-hand end of the solenoid in Figure 18.21 is a North pole.

True or false?

LINK PWB

Practical 18B, pp. XX–XX

What devices make use of electromagnetism?

Relay

A relay is a device that consists of two circuits (Figure 18.22). The primary circuit, controlled by a switch, is designed to work at a low, safe current. When the primary circuit is complete, the electromagnet is energised. The iron lever is attracted to the electromagnet and in moving, it pushes the moveable contact. This causes the moveable contact to touch the fixed contact, making the secondary circuit complete. The secondary circuit could contain a very much higher voltage supply and a high power device such as a motor.

The advantage of using a relay is that there is no electrical connection between the user activating the switch and the secondary circuit. The user can activate the device in the secondary circuit remotely. This is especially helpful if the device is somewhere that is otherwise unsafe for the user or is a large distance away.

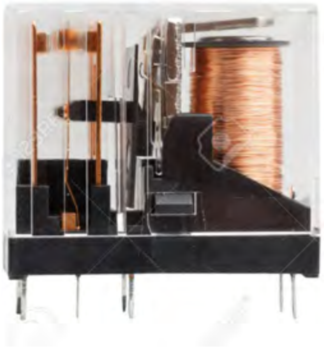


Photo of an electrical relay

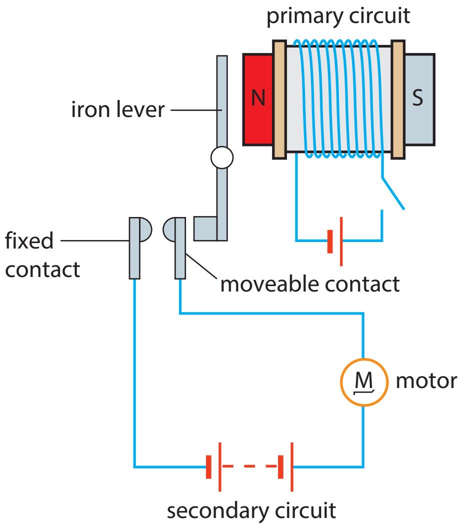


Diagram of a relay circuit

Figure 18.22 *Can you identify some parts of a relay in the photo.*

Moving-coil loudspeaker

Figure 18.23 shows how electromagnetism is used in a loudspeaker.

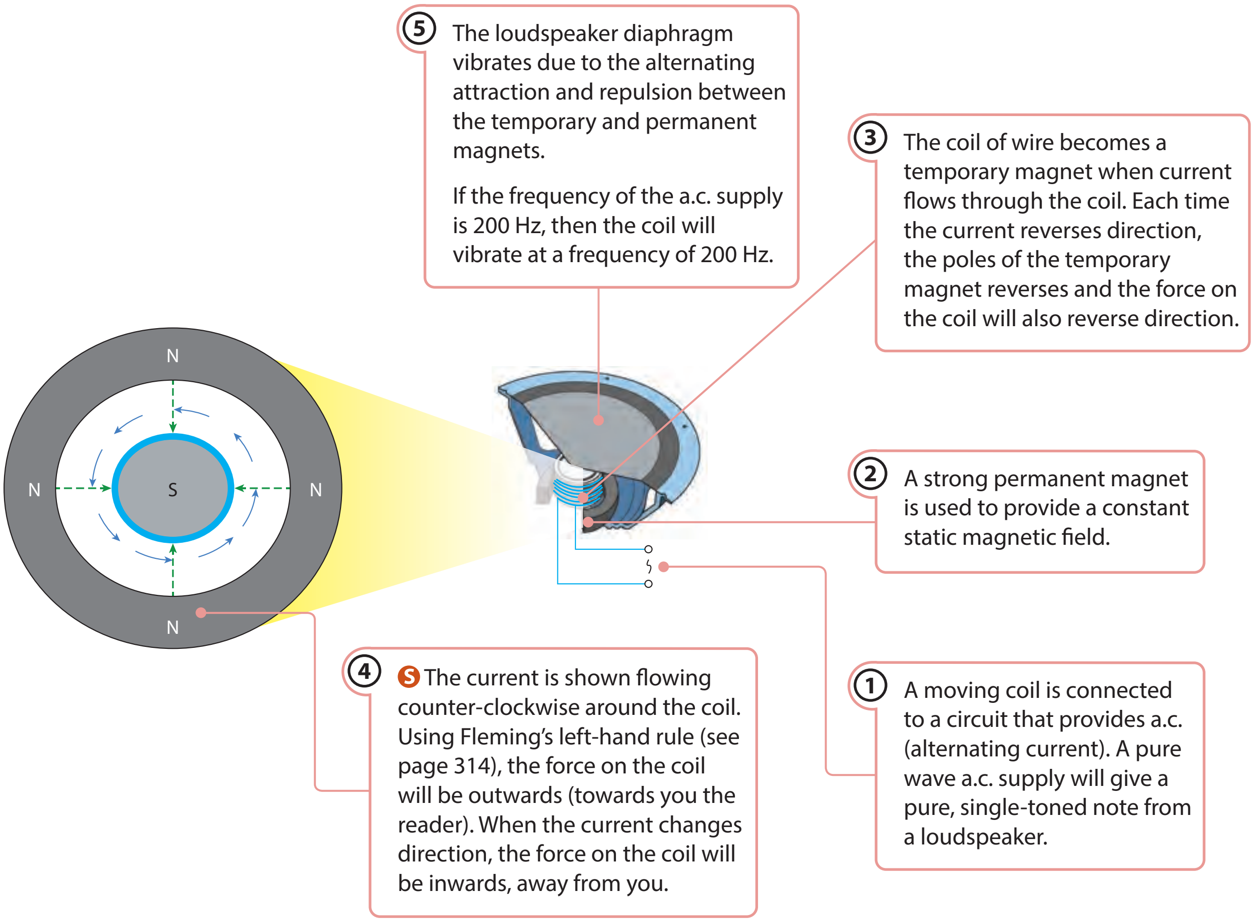


Figure 18.23 Use of electromagnet in a moving-coil loudspeaker

The magnetic component in the loudspeaker is designed so that the magnetic field lines are always at right angles to the current direction. This makes this design very much more efficient.

Let's Practise 18.3

1 Figure 18.24 shows a current flowing in a long straight wire. In the diagram, draw the pattern and direction of the magnetic field produced.

2 (a) Draw the magnetic field lines around a current-carrying solenoid.

(b) Name **three** ways to increase the magnetic field strength of a solenoid.

3 Explain what would happen if the iron core of the solenoid in a circuit breaker were replaced with a steel one.

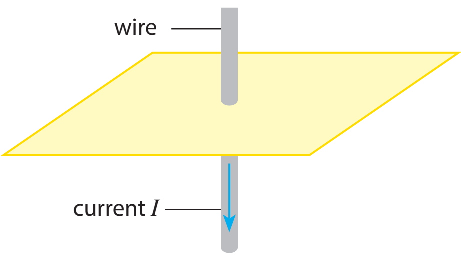


Figure 18.24

4 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

TWB **LINK**

Exercise 18C, pp. XX–XX

18.4 Force on a Current-carrying Conductor

In this section, you will learn the following:

- Describe an experiment to show that a force acts on a current-carrying conductor in a magnetic field.
- S Recall and use the relative directions of force, magnetic field and current.
- S Determine the direction of the force on beams of charged particles in a magnetic field.

Do current-carrying conductors affect each other?

In the previous section, you have learnt that a current-carrying wire produces a magnetic field around it. What happens if the current-carrying conductor is placed in another magnetic field?

Let's Investigate 18C describes an experiment to demonstrate the motor effect.

Let's Investigate 18B

Objective

To demonstrate that a force acts on a current-carrying conductor when it is placed in a magnetic field (i.e. the motor effect)

Apparatus

Stiff wire, strong permanent U-shaped magnet, 9 V dry cell, switch, connecting wires

Procedure

1 Bend a stiff wire into the shape of a swing ABCD (Figure 18.25).

2 Set up the apparatus as shown in Figure 18.25. The wire swing is connected to a dry cell and a switch by copper wires.

3 Close the switch. Observe the direction in which the wire swings.

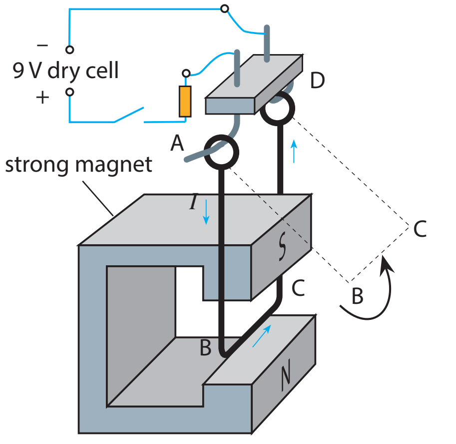


Figure 18.25 *A current-carrying wire swing placed in a magnetic field*

4 Reverse the polarity of the dry cell to reverse the direction of the current and repeat step 3. In which direction does the swing move now?

5 Invert the magnet so that the N pole is now above the wire section BC. Repeat step 3.

Observation

1 When current flowed in the direction A to B to C to D, the wire swung outwards, away from the magnet.

2 When the direction of the current was reversed, the wire swung in the opposite direction, i.e., it swung inwards, towards the magnet.

3 When the magnetic field was reversed, the wire swung outwards again.

In all three scenarios, we observe that the wire moved when current flowed through it. This shows that *a force acts on a current-carrying wire when it is placed in a magnetic field.*

LINK PWB

Practical 18C, pp. XX–XX

From Let's Investigate 18C, the following conclusions can be made:

- The direction of the force on a current-carrying conductor is reversed when we reverse the direction of the current or the magnetic field.
- The force, current and magnetic field are at right angles to one another.

Fleming's left-hand rule

We can deduce the direction of the force acting on a current-carrying conductor in a magnetic field using **Fleming's left-hand rule** (Figure 18.26).

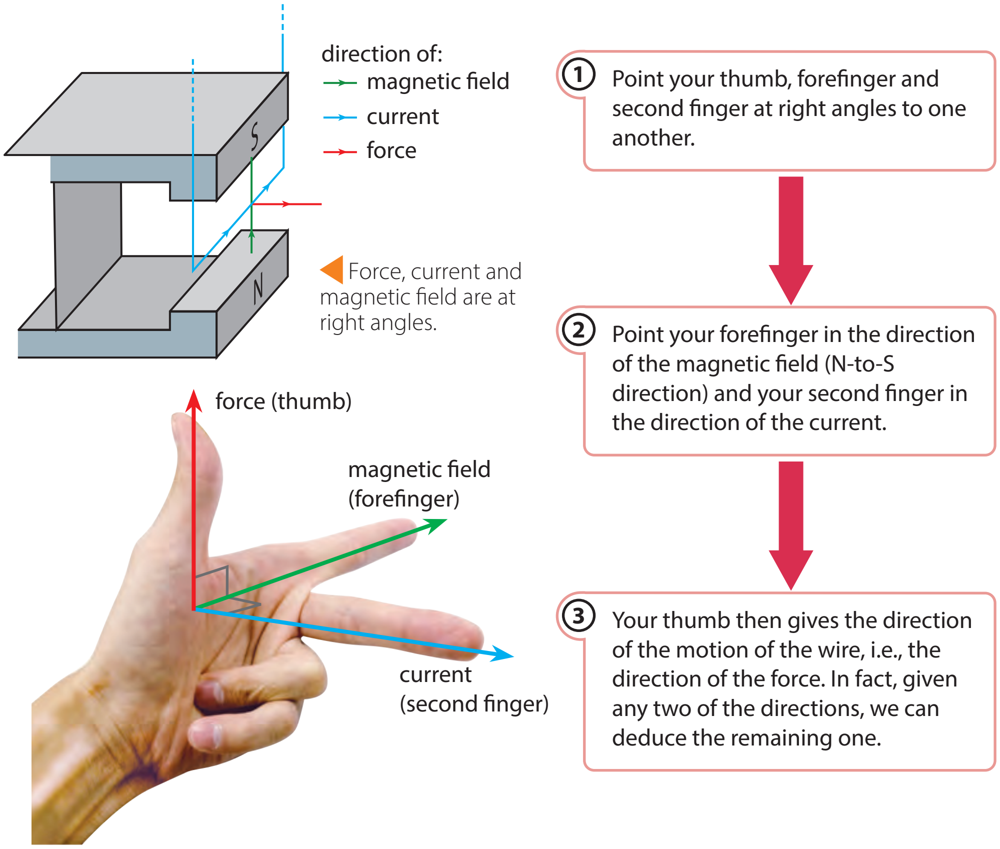


Figure 18.26 *Fleming's left-hand rule*

Worked Example 18C

Figure 18.27 shows a wire placed between two magnetic poles. State what happens when the current in the wire flows from

(a) A to B;

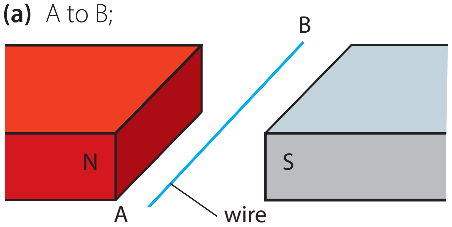


Figure 18.27

(b) B to A.

Solution

(a) When a current-carrying wire is placed in a magnetic field, a force acts on it. Using Fleming's left-hand rule, we find that the force acts vertically downwards on the wire (Figure 18.28).

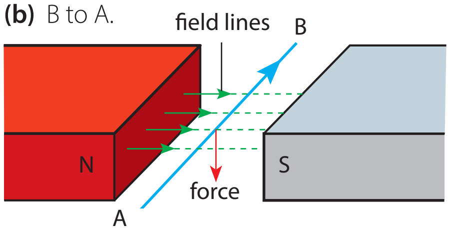


Figure 18.28 *The force acts vertically downwards when current flows from A to B.*

(b) Using Fleming's left-hand rule, we find that the force acts vertically upwards on the wire.

PHYSICS WATCH

Scan this page to explore a simulation on force on a current-carrying conductor.

What causes the motor effect?

Examine what happens when the magnetic field due to the current in a wire is combined with the magnetic field of a magnet (Figure 18.29).

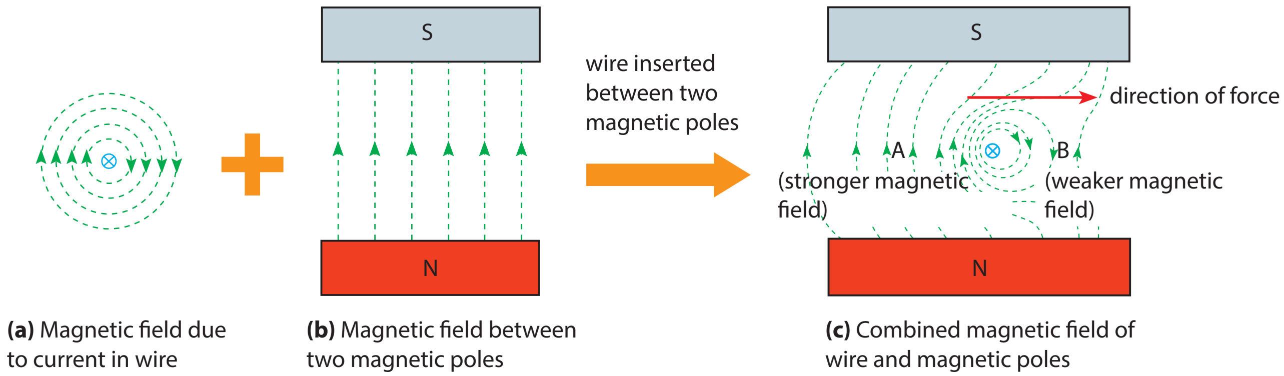


Figure 18.29 *How magnetic fields combine when a current-carrying wire is placed between the poles of a magnet*

From Figure 18.29(c), we can see that at point A, the magnetic fields produced by the current-carrying wire and by the magnetic poles act in the same direction. They reinforce each other and so the magnetic field at point A is stronger. At point B, the magnetic field of the current-carrying wire is in the opposite direction to the magnetic field of the magnetic poles. Thus, the combined magnetic field at point B is weaker.

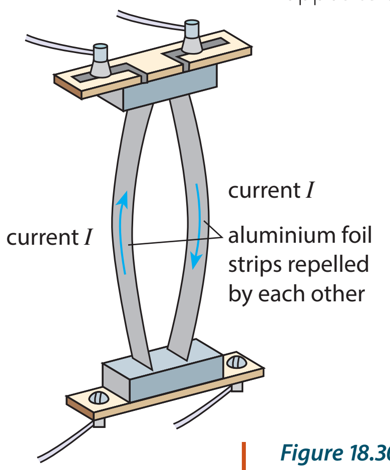
The *difference between the magnetic field strength* at A and at B results in a net force acting on the wire. The force acts towards the weaker field.

Forces between two parallel current-carrying conductors

When we place two current-carrying conductors parallel to each other, the magnetic fields of both wires *combine*. The combined magnetic field results in forces acting on each conductor.

Currents in opposite directions

Figure 18.30 shows the forces that act on two parallel strips of aluminium foil carrying currents in opposite directions.



Explanation: To understand the repulsion of the aluminium foil strips, consider the cross-section (top view) of a pair of parallel current-carrying wires.

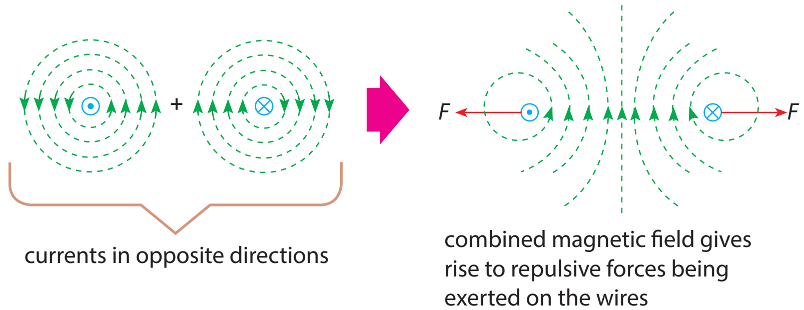
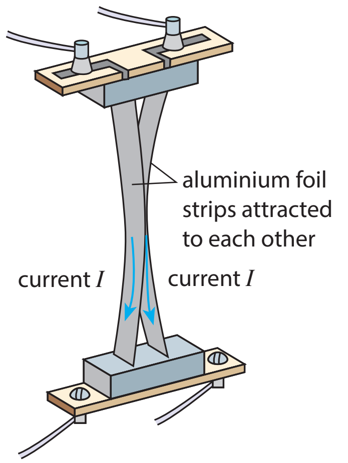


Figure 18.30 *Parallel aluminium foil strips carrying current in opposite directions repel each other.*

Conductors carrying currents in opposite directions repel.

Currents in same direction

Figure 18.31 shows the forces that act on two parallel strips of aluminium foil carrying currents in the same direction.



Explanation: To understand the attraction of the aluminium foil strips, consider the cross-section (top view) of a pair of parallel current-carrying wires.

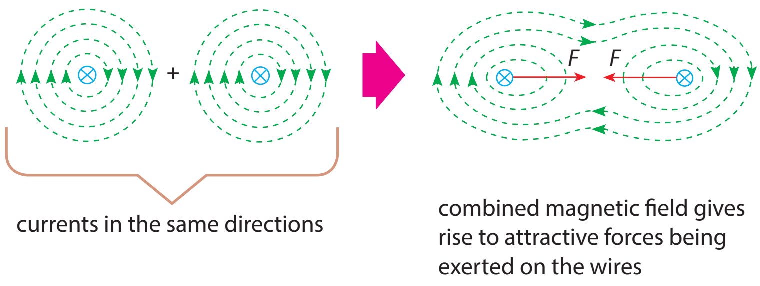


Figure 18.31 Parallel aluminium foil strips carrying currents in the same direction attract each other.

Conductors carrying currents in the same direction attract.

Force on a beam of charged particles in a magnetic field

In Chapter 17, you have learnt that current consists of moving charges. A current-carrying conductor experiences a force when placed in a magnetic field. Since a beam of charged particles is essentially a line of charged particles, we can examine the effects of a magnetic field on a beam of charged particles by examining the effect of a magnetic field on a single moving charge.

Positive charge moving in a magnetic field

Figure 18.32 shows the force acting on a positively charged particle moving through a magnetic field.

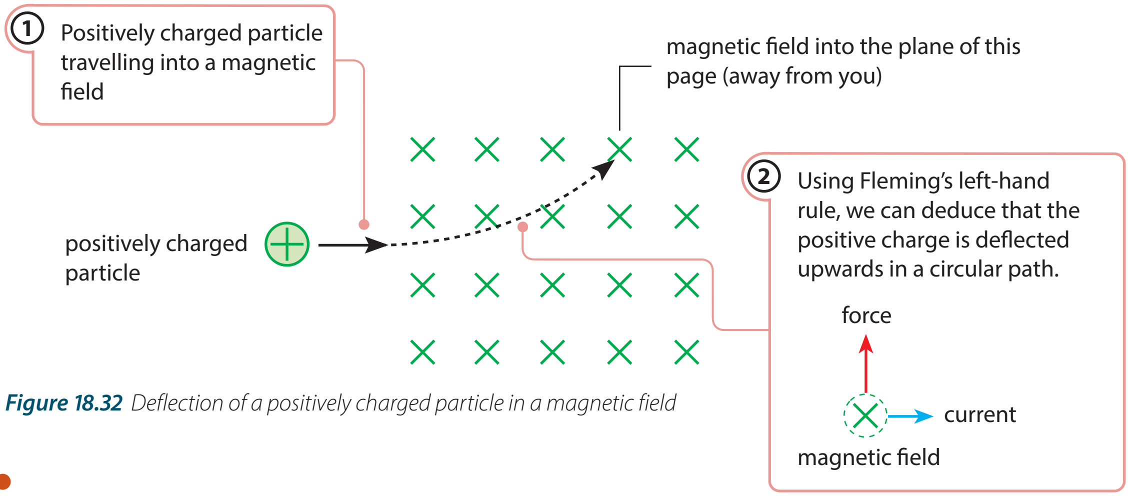


Figure 18.32 Deflection of a positively charged particle in a magnetic field

QUICK CHECK

A magnetic field can exert a force on a stationary charge.

True or false?

ENRICHMENT ACTIVITY

A mass spectrometer is a device that can work out the chemical composition of unknown substances.

Find out how a mass spectrometer uses a magnetic field to distinguish between chemical elements.

Share your findings with the class.

Negative charge moving in a magnetic field

Figure 18.33 shows what would happen to the force if the positive charge in Figure 18.32 were replaced with a negative charge (e.g. an electron).

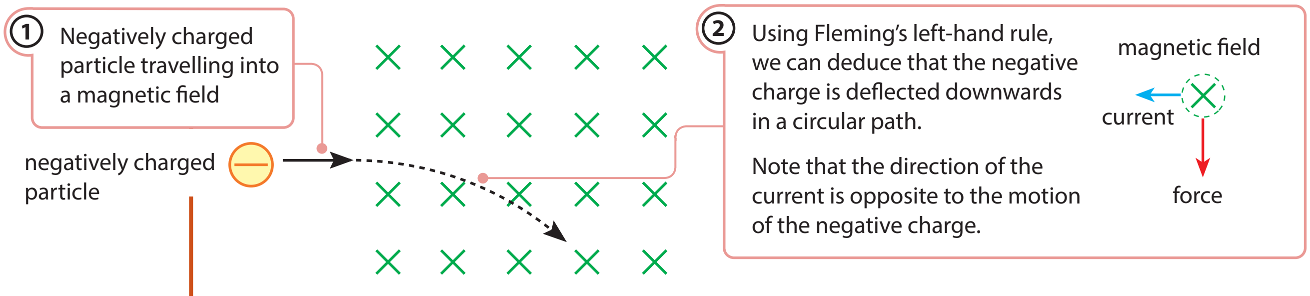


Figure 18.33 *Deflection of a negatively charged particle in the same magnetic field*

Reversing the magnetic field

Other than the charge of the particles, what do you think affects the direction of the force acting on the particles? Figure 18.34 shows what happens to the force acting on the positively charged particle (in Figure 18.33) if the magnetic field is reversed.

The direction of the force on a beam of charged particles is reversed when we reverse the direction of the magnetic field.

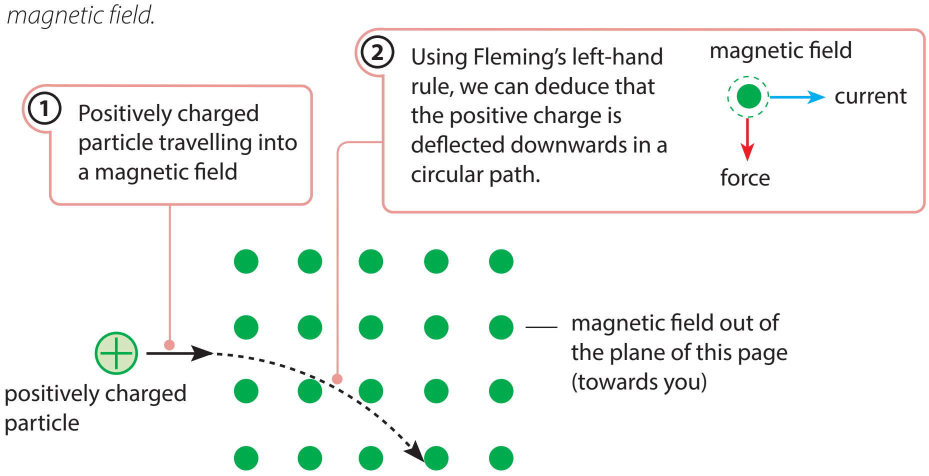


Figure 18.34 *The positively charged particle is deflected downwards when the magnetic field is reversed.*

Let's Practise 18.4

1 Figure 18.35 shows a current-carrying wire placed between the poles of a magnet.

(a) On the diagram, mark the direction of the force acting on the wire AB.

(b) Describe what happens to the motion of the wire AB if the poles of the magnets are reversed.

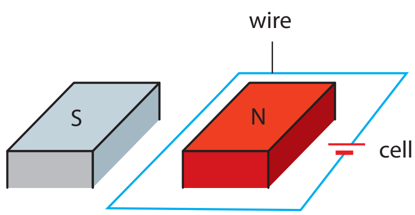


Figure 18.35

2 S Consider two parallel wires with currents flowing in the same direction.

(a) Draw a diagram showing the forces acting on each wire.

(b) State the change(s) that can be made to increase the magnitude of each force.

(c) Explain what will be observed if two current carrying wires are placed perpendicular to each other.

3 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

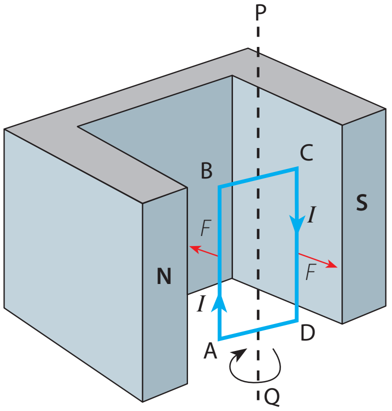
Exercise 18D, pp. XX–XX

18.5 The D.c. Motor

In this section, you will learn the following:

- Know that a current-carrying coil in a magnetic field experiences a turning effect and the factors that can increase the turning effect.
- S Describe the operation of an electric motor, including the action of a split-ring commutator and brushes.

In Section 18.4, you have learnt that a straight current-carrying wire placed between the poles of a magnet experiences a force. Figure 18.36 shows what happens if the straight current-carrying wire is replaced with a current-carrying wire coil.

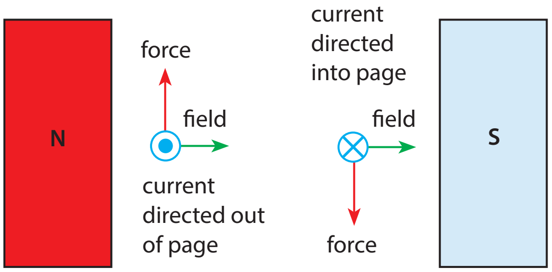


① A stiff wire coil ABCD is placed between the poles of a strong magnet. A current is passed through the coil.

② The coil experiences a **turning effect** about the axis PQ.

Figure 18.36 *Current-carrying wire coil placed between two magnetic poles*

What causes the turning effect of coil ABCD in the set-up in Figure 18.36? To understand this turning effect, we consider the top view of the cross-section of the set-up (Figure 18.37).



The two forces produce a turning effect.
Note: Fleming's left-hand rule was used to deduce the directions of the forces on wire sections AB (current out of page) and CD (current into page).

Figure 18.37 *Top view of cross-section of set-up in Figure 18.36*

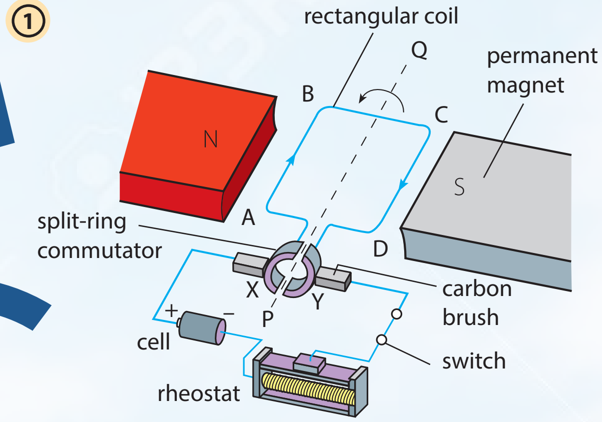
The turning effect on a current-carrying wire coil can be increased by increasing

- the number of turns in the wire coil;
- current in the wire coil;
- the strength of the magnetic field.

S The d.c. motor

An important application of the turning effect on a current-carrying coil in a magnetic field is the **direct current (d.c.) motor**. A d.c. motor is used to convert electrical energy to mechanical energy. It is commonly used in battery-operated toys, DVD players and hard disk drives. Figure 18.38 shows how a d.c. motor works.

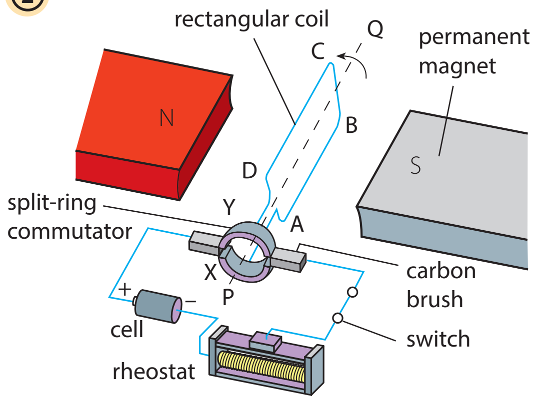
a d.c. motor



Structure of a d.c. motor:

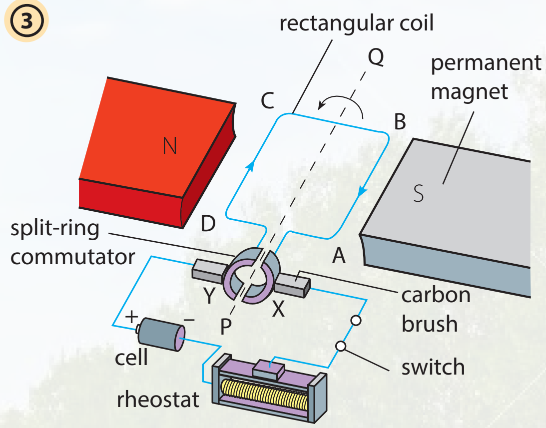
1. A rectangular wire coil ABCD is mounted on an axle (represented by the dotted line PQ) that allows it to rotate about PQ.
2. The coil and the axle are positioned in between the poles of a permanent magnet.
3. The ends of coil ABCD are connected to a split-ring commutator XY. The commutator rotates with the coil.
4. Two carbon brushes press lightly against the commutator.

Using Fleming's left-hand rule, we know that a downward force acts on wire section AB, and an upward force on wire section CD. The coil thus rotates anticlockwise about PQ until it reaches a vertical position.



- When the coil is in the vertical position, the current is cut off because the split ring commutator XY is not in contact with the carbon brushes.
- The momentum of the coil, however, carries it past the vertical position.

it is common to find d.c. motors in small devices.



- The direction of the currents flowing through wire sections AB and CD is now reversed. An upward force now acts on AB, and a downward force acts on CD.
- Hence, the coil continues to rotate in the anticlockwise direction.

Figure 18.38 *How a d.c motor works*

In a d.c. motor, the function of the split-ring commutator is to reverse the direction of the current in the coil every half a revolution. This occurs whenever the commutator changes contact from one brush to the other. This ensures that the coil will always turn in one direction.

The turning effect on a current-carrying coil in a d.c. motor can be increased by

- inserting a soft iron core into the coil;
- increasing the number of turns in the coil;
- increasing the current in the coil.

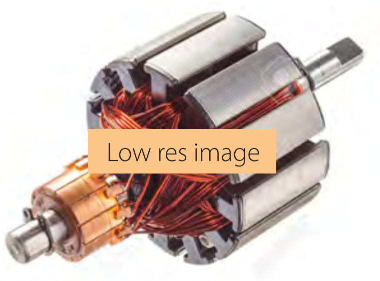


Figure 18.39 *Practical d.c. motors, like the one shown above, have hundreds of turns of wire with a soft iron core at the centre.*

ENRICHMENT *THINK*

Refer to Figure 18.39. Why are the iron parts curved?

Let's Practise 18.5

1. The coil in a particular d.c. motor rotates in an anticlockwise direction. State the change(s) that must be made in order for the coil to rotate in a clockwise direction.
2. Explain the purpose of the rheostat in the d.c. motor.
3. State the energy conversion that takes place in the d.c. motor.
4. **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK

Exercise 18E, pp. XX–XX

18.6 The Transformer

In this section, you will learn the following:

- Describe the construction of a simple transformer with a soft iron core, as used for voltage transformations.
- S Explain the principle of operation of a simple iron-cored transformer.
- Use the terms *primary*, *secondary*, *step-up* and *step-down*.
- Recall and use the equation $\frac{V_p}{V_s} = \frac{N_p}{N_s}$ where *p* and *s* refer to primary and secondary.
- Describe the use of transformers in high-voltage transmission of electricity.
- State the advantages of high-voltage transmission.
- S Recall and use the equation for 100% efficiency in a transformer, $I_pV_p = I_sV_s$.
- S Recall and use the equation $P = I^2R$ to explain why power losses in cables are smaller when the voltage is greater.

LINK

Recall that a current-carrying conductor produces a magnetic field.

Refer to Chapter 15.

In 1831, Faraday discovered that when two coils of wire were wrapped around a soft iron ring (Figure 18.40), the magnetic field produced by one coil could induce a current in the other. A compass was placed above wire PQ to detect any changes in the magnetic field there. If the needle of the compass was deflected, it meant there was a magnetic field present. This indicated that there was a current flowing in the wire PQ.

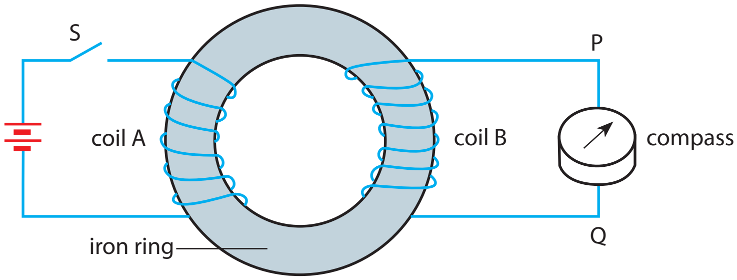


Figure 18.40 *Faraday's iron ring experiment*

QUICK CHECK

The compass remains deflected when there is a constant current in coil A.

True or false?

Figure 18.41 summarises the results of Faraday's experiment.

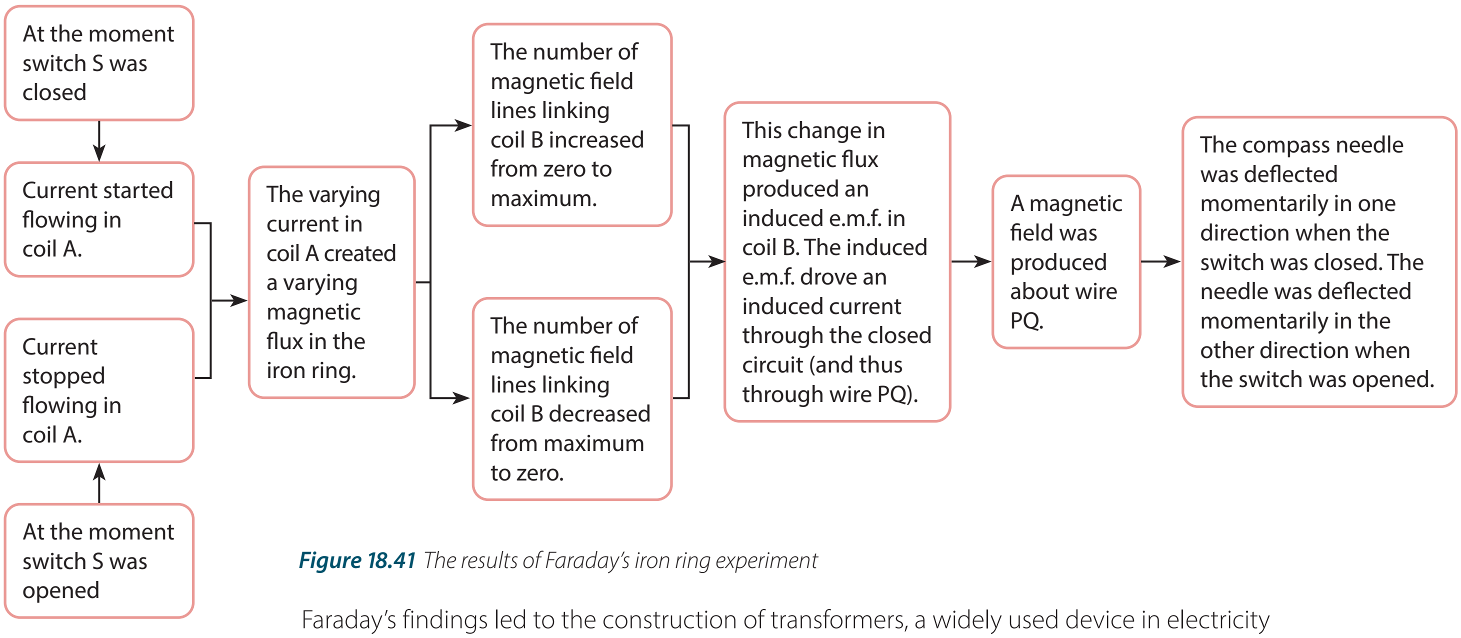


Figure 18.41 *The results of Faraday's iron ring experiment*

Faraday's findings led to the construction of transformers, a widely used device in electricity transmission. In the following sections, you will learn what transformers are and how they work.

What is a transformer?

The mains supply voltage for homes in many Asian countries such as Singapore is between 220 V and 240 V. However, different electrical appliances operate at different voltages. For example, a typical mobile phone only needs about 5 V. To convert the mains supply voltage to a suitable voltage for different appliances, transformers are used.

A **transformer** is a device that can change a high alternating voltage (at low current) to a low alternating voltage (at high current), or vice versa.

Transformers are used in

1. electrical power transmission from power stations to households and industries;
2. regulating voltages for the proper operation of electrical appliances.

Structure and operation of a transformer

The structure (Figure 18.42) and workings of a transformer are based on Faraday's findings in the iron ring experiment.

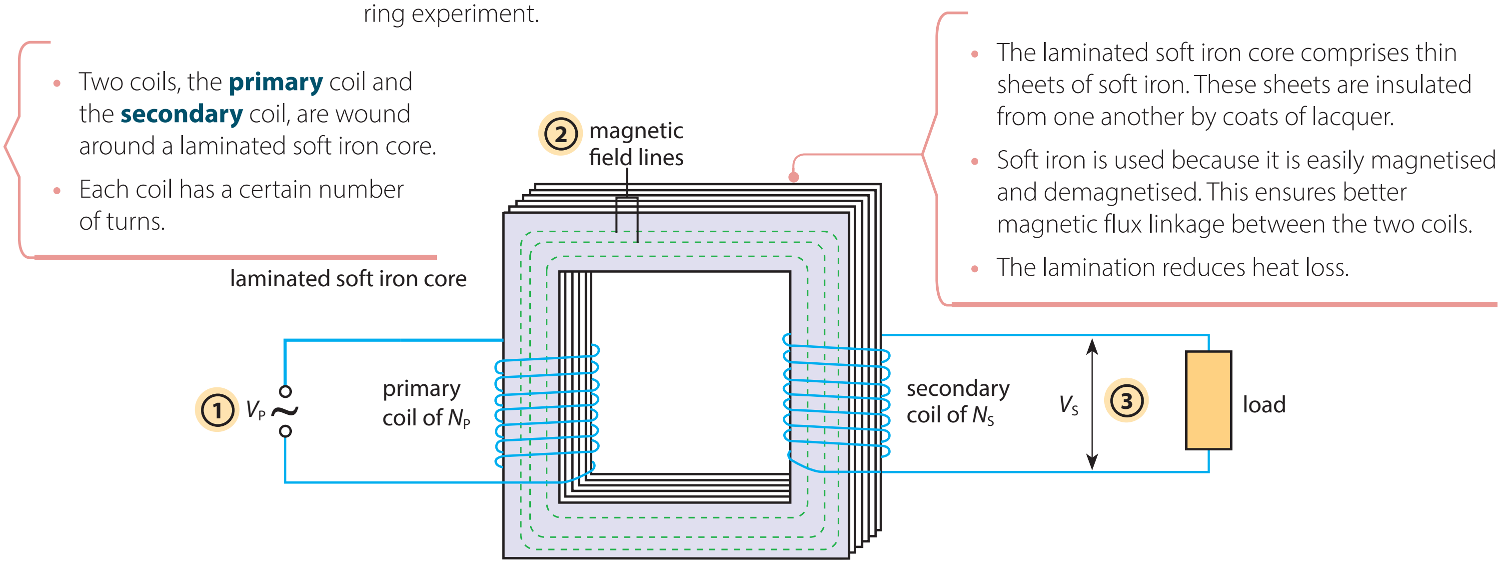


Figure 18.42 *Structure of a transformer*

The workings of a transformer are as follows (refer to Figure 18.42):

① The primary coil is connected to an alternating voltage — the **input voltage** V_P. → ② A varying magnetic field is set up in the laminated soft iron core. → ③ An e.m.f. V_S is induced in the secondary coil. This voltage is called the **output voltage**. Since the circuit is closed, a current is also induced in the coil.

Electrical energy is transferred from the primary coil to the secondary coil in a transformer. The voltages and the number of turns in the primary and secondary coils are related by this formula:

$$\frac{V_P}{V_S} = \frac{N_P}{N_S}$$

where V_S = secondary (output) voltage (in V)
V_P = primary (input) voltage (in V)
N_S = number of turns in secondary coil
N_P = number of turns in primary coil

QUICK CHECK

$\frac{N_P}{N_S}$ for a step-up transformer is less than 1.

True or false?

In a **step-up** transformer, the number of turns in the secondary coil is greater than that in the primary coil. This results in an output voltage that is higher than the input voltage.

In a **step-down** transformer, the converse is true. The number of turns in the secondary coil is less than that in the primary coil, so that the output voltage produced is lower than the input voltage.

Power transmission in a transformer

In an ideal transformer, there is no power loss (i.e. the efficiency is 100%). The power supplied to the primary coil is fully transferred to the secondary coil. Hence, from the principle of conservation of energy, power in the primary coil = power in the secondary coil.

$$I_P V_P = I_S V_S$$

where V_S = secondary (output) voltage (in V)
V_P = primary (input) voltage (in V)
I_S = current in secondary coil (in A)
I_P = current in primary coil (in A)

LINK

Recall the equation $P = IV$ which you have learnt in Chapter 16.

From the equations $\frac{V_P}{V_S} = \frac{N_P}{N_S}$ and $I_P V_P = I_S V_S$,

we can obtain the equation $\frac{V_P}{V_S} = \frac{N_P}{N_S} = \frac{I_S}{I_P}$.

Therefore, $V_S = \left(\frac{N_S}{N_P}\right) V_P$ and $I_P = \left(\frac{N_S}{N_P}\right) I_S$.

We can see that for a step-up transformer:

1 $V_S > V_P$ by the fraction $\frac{N_S}{N_P}$;

2 $I_S < I_P$ by the same fraction $\frac{N_S}{N_P}$.

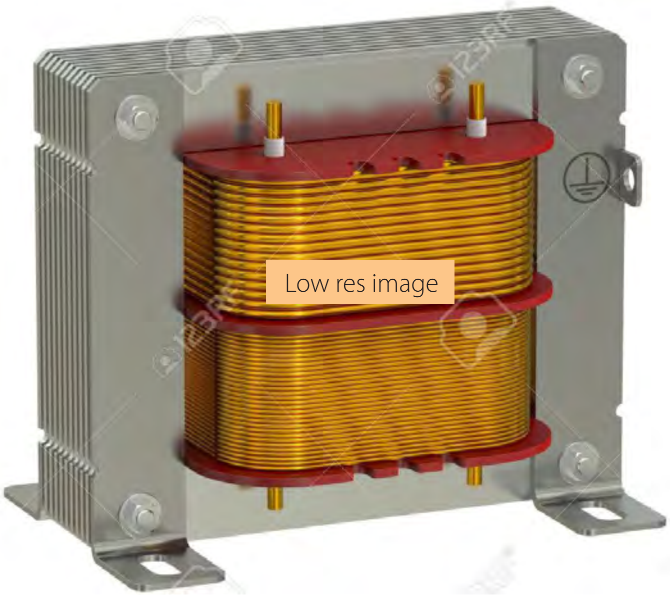


Figure 18.43 A transformer — the coils and laminated soft iron core can be seen. The design of this transformer differs from the one shown in Figure 18.42. What other designs are there, and why?

S

The converse is true for a step-down transformer (Table 18.3).

Table 18.3 Comparing step-up and step-down transformers

Step-up transformer	Step-down transformer
$N_s > N_p$	$N_s < N_p$
$V_s > V_p$	$V_s < V_p$
$I_s < I_p$	$I_s > I_p$

LINK

Recall about mechanical efficiency which you have learnt in Chapter 6.

In reality, transformers are not ideal. There is power loss, and therefore the efficiency is less than 100%. The efficiency of a transformer can be calculated using the following equation:

$$\textbf{Efficiency} = \frac{\textbf{output power}}{\textbf{input power}} \times 100\%$$

Worked Example 18D

The circuit shown in Figure 18.44 is set up.

(a) Explain briefly how a transformer works.

(b) Assuming the transformer in Figure 18.44 is 100% efficient, complete Table 18.4.

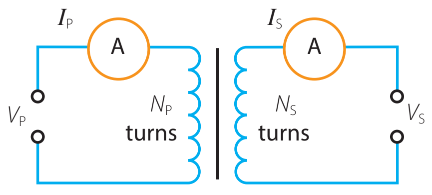


Figure 18.44

Table 18.34

V_p/V	I_p/mA	N_P turns	V_S/V	I_s/mA	N_s turns
240	2			40	50

(c) Is the transformer a step-up or step-down transformer?

(d) The transformer used in the experiment is actually non-ideal. It is found that when the primary current is 2 mA, the secondary current is 30 mA instead of 40 mA. Assuming that the secondary voltage V_S is the same as that calculated in **(b)**, calculate the efficiency of this practical transformer.

Solution

(a) The operation of a transformer is based on electromagnetic induction. An alternating current in the primary coil induces a varying magnetic field in the soft iron core. This varying magnetic field creates an alternating induced e.m.f. in the secondary coil, which generates an induced current.

(b) At 100% efficiency,

input power of primary coil = output power of secondary coil

$I_P V_P = I_S V_S$

$$V_S = \frac{I_P V_P}{I_S} = \frac{2\text{ mA} \times 240\text{ V}}{40\text{ mA}} = 12\text{ V}$$

$$\text{Using } \frac{V_P}{V_S} = \frac{N_P}{N_S},\ N_P = \frac{V_P N_S}{V_S} = \frac{240\text{ V} \times 50\text{ turns}}{12\text{ V}} = 1000\text{ turns}$$

(c) Since the number of turns in the secondary coil is less than the number of turns in the primary coil (i.e. $N_s = 50 < N_P = 1000$), the transformer is a step-down transformer.

(d) By definition,

$$\text{efficiency} = \frac{\text{output power in secondary coil}}{\text{input power in primary coil}} \times 100\%$$

$$= \frac{I_S V_S}{I_P V_P} \times 100\% = \frac{30\text{ mA} \times 12\text{ V}}{2\text{ mA} \times 240\text{ V}} \times 100\% = 75\%$$

Transformers and the transmission of electricity

There are problems in the transmission and distribution of electricity from power stations to households and industries. One of them is the *loss of power due to Joule heating* ($P = I^2R$) in the cables. This loss should be minimised for efficiency and economy.

Possible solutions:

- Use very thick cables, so that the resistance R is low. In this way, the power lost as heat in the cables is reduced. However, thicker cables increase the cable and construction costs.
- Reduce the magnitude of the current I flowing in the cables. This can be done with a step-up transformer. When the transmission voltage V is stepped up, the current I in the cables is stepped down.

HELPFUL NOTES

Voltage does not contribute to the power loss due to Joule heating. However, the output voltage affects the output current. So, we can adjust the output voltage (by adjusting the number of turns in the secondary coil of a transformer) to adjust the output current.

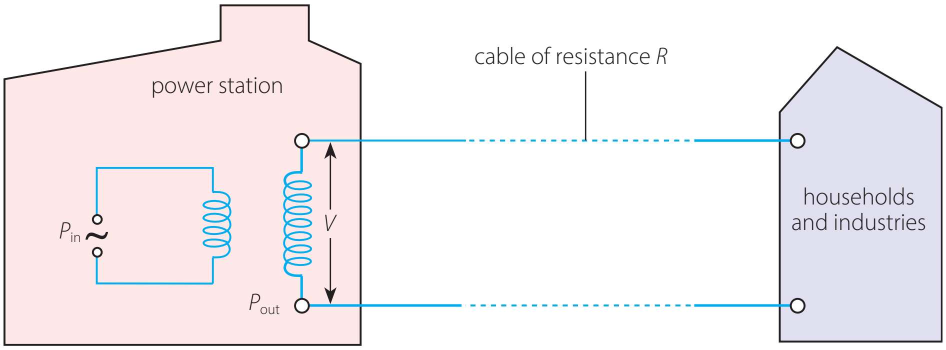


Figure 18.45 *Power transmission*

S

Suppose the electrical power output P_{out} of a power station is to be transmitted at a voltage V by transmission cables of total resistance R (Figure 18.45). The current I in the transmission cables is

$$I = \frac{P_{out}}{V}.$$

Hence, the power lost as thermal energy, P_{loss}, is

$$P_{loss} = I^2R = \left(\frac{P_{out}}{V}\right)^2 R.$$

Thus, the greater the value of V, the lower the power loss.

As electricity is transmitted more efficiently at high voltages, electricity produced in power stations has its voltage stepped up by step-up transformers. The high-voltage electricity is then transmitted to households and industries through transmission cables. Step-down transformers then reduce the voltage to suitable values so that households and industries can use the electricity safely.

Figure 18.46 *Step-down transformers help distribute electricity to households and industries.*

ENRICHMENT THINK

Overhead transmission cables are supported by electricity pylons. In some countries, most transmission cables are underground. Why?

Worked Example 18E

A power station with an output power of 100 kW at 20 000 V is connected by cables to a factory.

(a) If the resistance of the cables is 5.0 Ω, calculate the

(i) current flowing in the cables;

(ii) power loss in the cables.

(b) Account for the power loss.

Solution

Given: Output power $P_{out} = 100 \times 10^3$ W

Voltage $V = 20\ 000$ V

Resistance R of cables = 5.0 Ω

(a) **(i)** Since $P_{out} = V\boldsymbol{I}$, where $\boldsymbol{I}$ is the current in the cables,

$$\boldsymbol{I} = \frac{P_{out}}{V} = \frac{100 \times 10^3 \text{ W}}{20\ 000 \text{ V}} = 5 \text{ A}$$

(ii) Power loss in the cables

$P_{loss} = \boldsymbol{I}^2R = (5 \text{ A})^2 \times 5.0\ \Omega = 125$ W

(b) Power is lost as thermal energy. This is due to Joule heating, caused by the resistance of the cables and the current flowing through the cables.

Let's Practise 18.6

Figure 18.47 shows a simple transformer.

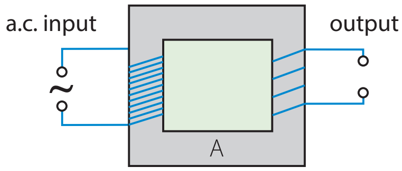


Figure 18.47

1 **(a)** Explain

(i) the material used to make the item labelled A;

(ii) whether the output voltage is greater or smaller than the input voltage.

(b) Ⓢ This transformer supplies a voltage of 12 V to a model train, which draws a current of 0.8 A. If the voltage of the a.c. source is 240 V, calculate the current in the primary coil.

2 Power is lost as thermal energy during the transmission of electricity from power stations to homes. State **two** ways through which this power loss can be minimised.

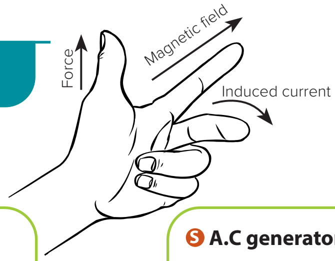
3 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

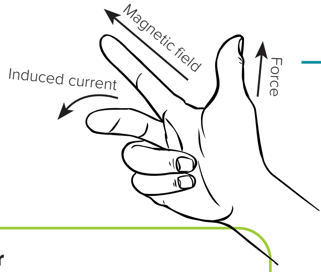
LINK TWB

Exercise 18F–18G, pp. XX–XX

Exercise 18H Let's Reflect

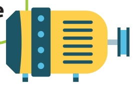
Let's Map It





ELECTROMAGNETIC EFFECTS

S D.C. motors
- Convert electrical energy into mechanical energy
- Direction of resultant force can be found using **Fleming's left-hand rule**



applied in

Turning effect

produces

Current-carrying conductor in an external magnetic field

can be increased by increasing

- The number of turns on the coil
- The current
- The strength of the magnetic field

S Beams of charged particles in a magnetic field

S Two parallel current-carrying conductors in a magnetic field

acts on

Resultant force

Electromagnetism

involves interaction of

Interact to produce

External magnetic fields

Magnetic fields

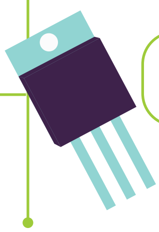
produces

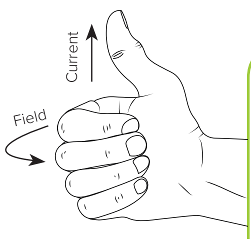
Electric current

applied in

- Relays
- Loudspeakers

Field patterns can be deduced using the **right-hand grip rule**.





- Magnetic field strength can be increased by increasing the magnitude of the current
- Magnetic field direction can be reversed by reversing the direction of the current

S A.C generator
- Convert mechanical energy into electrical energy
- Direction of induced current in the coil can be found using **Fleming's right-hand rule**

applied in

Electromagnetic induction
- A process in which an induced e.m.f. is produced in a conductor due to a changing magnetic field.

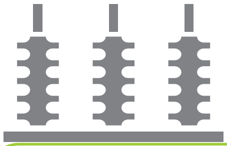
governed by

S Lenz's law
- The direction of an induced e.m.f. opposes the change that is causing it.

Faraday's law
- The magnitude of the induced e.m.f. in a circuit is directly proportional to the rate of change of magnetic flux in the circuit .

Factors affecting the magnitude of an induced e.m.f.
- Number of turns in the current-carrying coil
- Strength of the magnet
- Speed at which the magnet moves with respect to the current-carrying conductor

applied in



Transformer
- Change a high alternating voltage (at low current) to a low alternating voltage (at high current) or vice versa

used for

High voltage transmission of electricity
- Reduce power losses (more efficient)

  S $P_{loss} = I^2R = (\frac{P_{out}}{V})^2R$
- Lower cable and construction costs

- Turns ratio $\frac{V_p}{V_s} = \frac{N_p}{N_s}$ where p means primary and s means secondary
- S For an ideal transformer (100% efficiency), $I_p V_p = I_s V_s$

Let's Review

Section A: Multiple-choice Questions

1 Figure 18.48 shows a current-carrying wire passing through the centre of a sheet of cardboard. How do the strengths of the magnetic field at points X, Y, and Z compare?

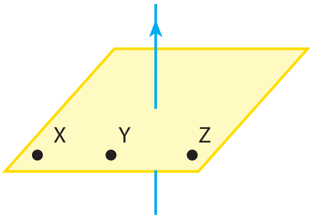


Figure 18.48

A Different at X, Y, and Z
B Equal at X and Z, but stronger at Y
C Equal at X and Z, but weaker at Y
D Stronger at X than Y, and stronger at Y than Z

2 In Figure 18.49, a current-carrying wire is placed between two magnetic poles. In which direction does the wire move?

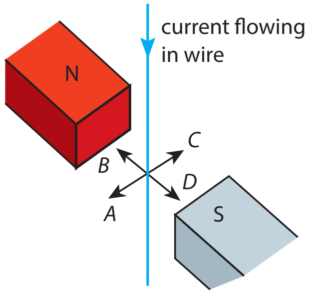


Figure 18.49

3 Figure 18.50 shows a current-carrying coil placed within a magnetic field. The coil experiences forces that make it move. How does the coil move?

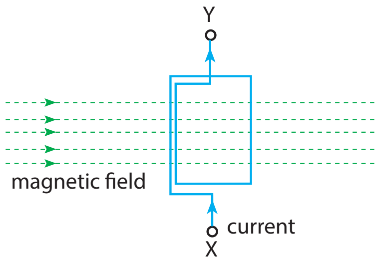


Figure 18.50

A From X to Y
B Out of page
C Along the magnetic field
D About the axis XY

4 Figure 18.51 shows a beam of electrons entering a magnetic field.

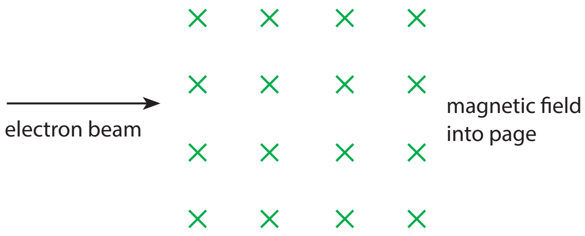


Figure 18.51

What is the initial direction of the deflection of the electrons as the beam passes through the field?

A Into page
B Out of page
C Towards the bottom of page
D Towards the top of page

5 In a simple d.c. motor, the direction of current in the motor coil is reversed every half-revolution. This is to keep the coil turning in the same direction. Which part of the motor enables this?

A Brushes
B Coil
C Split-ring commutator
D Permanent magnets

6 Which of the following procedures does not generate an e.m.f.?

A Holding a magnet stationary inside a coil
B Rotating a coil in a magnetic field
C Rotating a magnet around a stationary coil
D Moving a bar magnet across a flat piece of metal

7 In electromagnetic induction, which of the following does not affect the magnitude of the induced e.m.f.?

A The strength of the magnetic field linking the coil
B The resistance of the coil cutting across the magnetic field
C The speed with which the coil cuts across the magnetic field
D The number of turns in the coil

8 S Figure 18.52 shows the coil of a generator with slip rings.

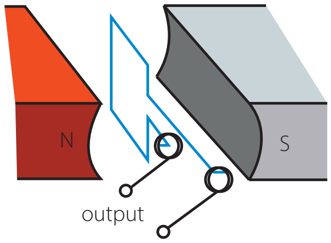
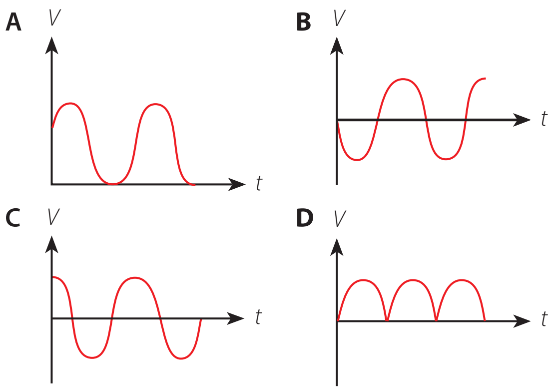


Figure 18.52

Which of the following graphs gives the correct output voltage against time when the coil begins to turn from the position shown?



9 S Why is soft iron used in the core of a transformer?

A It has a low electrical resistance.

B It conducts the induced current well.

C It does not melt easily when the induced current is too large.

D It ensures better magnetic flux linkage between the two coils.

Section B: Short-answer and Structured Questions

1 **(a)** Using suitable diagrams, describe the pattern of the magnetic field due to the current in a

(i) long straight wire;

(ii) solenoid.

(b) S State a factor that affects the strength of the magnetic field of a current-carrying conductor, and describe how it affects the magnetic field strength.

(c) S State a factor that affects the direction of the magnetic field of a current-carrying conductor, and describe how it affects the magnetic field direction.

2 **(a)** What is electromagnetic induction?

(b) State the factors that affect the magnitude of the induced e.m.f.

3 Referring to Figure 18.53, state what is observed in the galvanometer when the

(a) magnet is moved into the solenoid;

(b) magnet is pulled out of the solenoid;

(c) number of turns in the solenoid is increased and **(a)** is repeated.

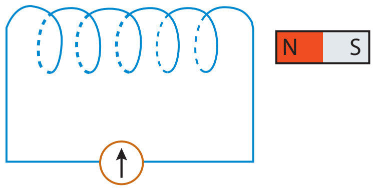


Figure 18.53

4 S

(a) State Lenz's Law of electromagnetic induction.

(b) Explain how Lenz's Law illustrates the principle of conservation of energy.

5 S

(a) Draw a labelled diagram of a simple a.c. generator and describe the use of the slip rings.

(b) Sketch the graph of the output voltage against time for a simple a.c. generator.

6 Figure 18.54 shows a solenoid connected to a galvanometer.

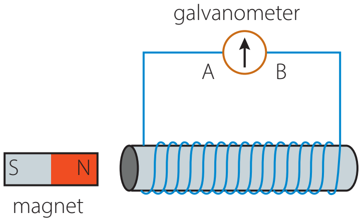


Figure 18.54

Explain the following observations:

(a) When the magnet is held stationary at the end of the coil, the galvanometer needle is not deflected.

(b) When the magnet is moved towards the solenoid, the galvanometer needle is deflected towards A.

(c) The faster the motion of the magnet towards the solenoid, the larger the deflection of the galvanometer needle.

(d) When the magnet is moved away from the solenoid, the galvanometer needle is deflected towards B.

Let's Review

7 Ⓢ A transformer has 400 turns in the primary coil and 10 turns in the secondary coil. The primary voltage is 250 V and the primary current is 2.0 A.

(a) Calculate the

(i) secondary voltage;

(ii) secondary current, assuming the transformer is ideal.

(b) Several measures are taken to increase the efficiency of transformers. Explain why, and describe **two** features in transformer design that improve efficiency.

8 A battery charger draws electricity from the 240 V mains supply. The charger contains a transformer, which provides an output of 15 V.

(a) There are 6400 turns on the primary coil of the transformer. Calculate the number of turns on the secondary coil.

(b) Ⓢ Assuming that the transformer is 100% efficient, calculate the current flowing in the primary coil if the output current of the transformer is 2.0 A.

9 Figure 18.55 shows part of a power transmission system. Electricity from the power station is transmitted to end users via transmission cables. The power station has a capacity of 200 MW and produces a voltage of 2 kV. The transmission cable is at 400 kV. The end users receive a voltage of 250 V.

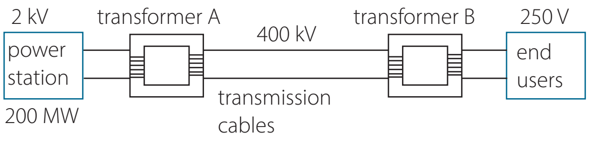


Figure 18.55

(a) Is transformer A a step-up or a step-down transformer? Explain your answer.

(b) Ⓢ Assuming that transformers A and B are ideal, and that no energy is lost during transmission, calculate the

(i) current flowing through the transmission cables;

(ii) total current supplied to the end users;

(iii) total energy generated by the power station each day.

(c) Ⓢ Why is electricity transmitted at high voltage?

10 Ⓢ

(a) What is Fleming's left-hand rule used for?

(b) On Figure 18.56, label the following parts:

(i) Split-ring commutator

(ii) Carbon brushes

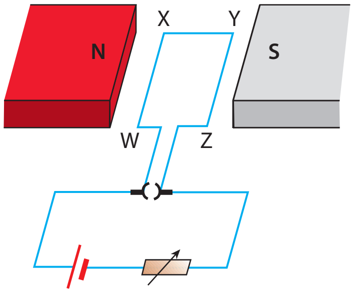


Figure 18.56

(c) What are the functions of the parts in **(b)(i)** and **(ii)**?

(d) Using Fleming's left-hand rule, state whether the rectangular coil will rotate clockwise or anticlockwise. Draw the forces that cause the rotation on the diagram.

(e) How would you change the direction of rotation of the coil?

11 A wire is wound 30 times around a soft iron C-core (Figure 18.57).

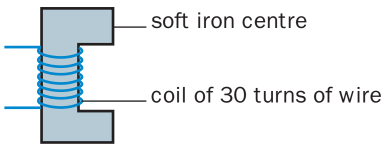


Figure 18.57

You are provided with two such C-cores.

(a) Without the use of a magnet, describe how you would use the C-cores to show that a current can be induced in a coil of wire through electromagnetic induction.

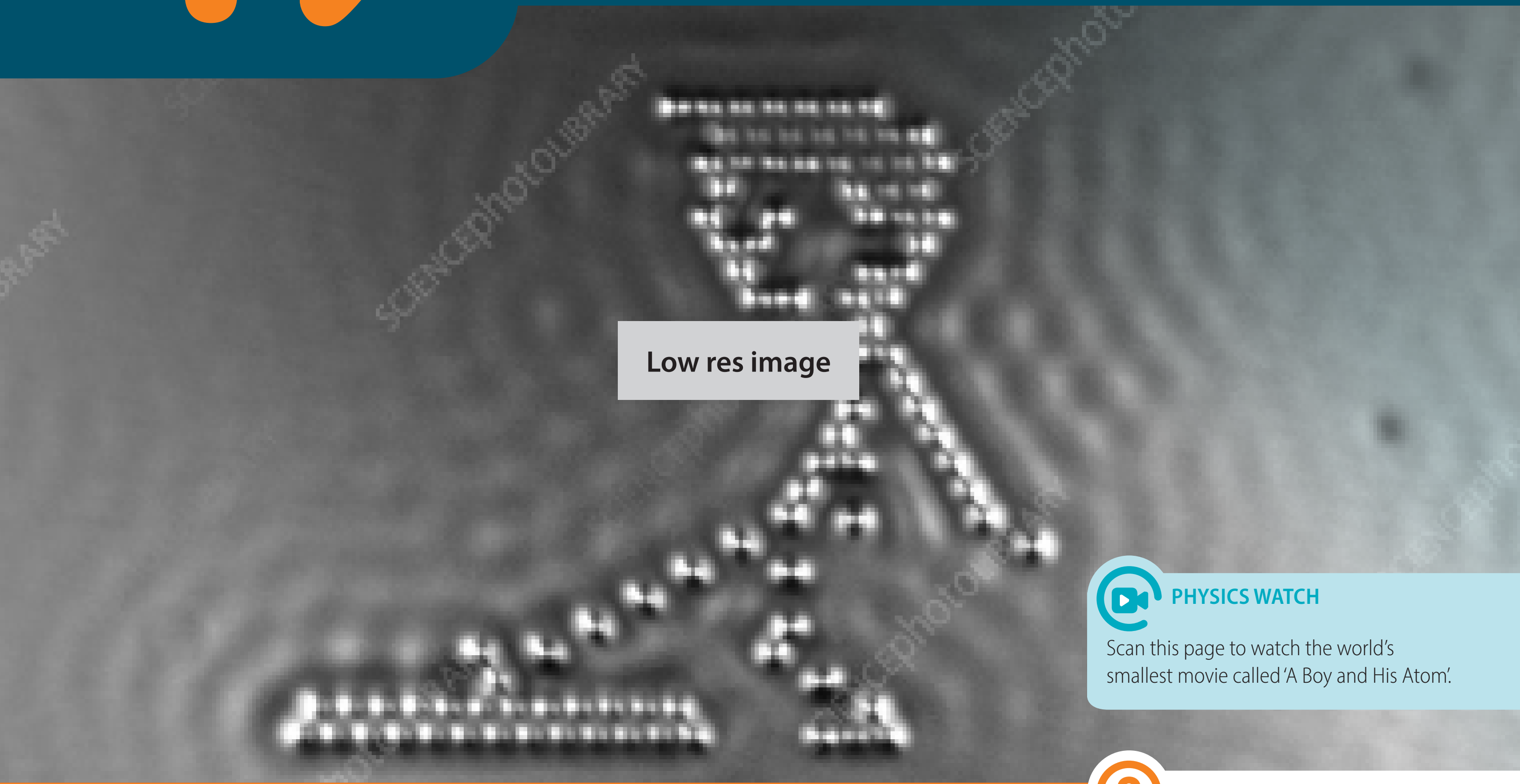
(b) Should the wires that are wound around the soft iron C-cores be insulated? Why?

12 **(a)** Describe an experiment to demonstrate electromagnetic induction. Explain how you would demonstrate the factors that affect the magnitude and the direction of the induced e.m.f.

(b) Ⓢ Describe briefly how electromagnetic induction is applied in the operation of a transformer.

CHAPTER 19

Nuclear Model of the Atom



PHYSICS WATCH

Scan this page to watch the world's smallest movie called 'A Boy and His Atom'.

QUESTIONS

- What do you think atoms look like?
- The photo shows raised dots that make up the image of the boy. What are these raised dots caused by?
- How can atoms help to solve our data storage needs?

We are creating more and more data every day. How do we solve the problem of where to store this huge amount of data? Scientists have explored right down to the atomic level to find a solution for data storage.

The photo shows an image of a boy taken from a 1-minute movie called *A Boy and His Atom*, made by researchers at IBM. The movie was made by moving carbon monoxide molecules using a scanning tunneling microscope. The microscope can magnify atoms 100 million times. It is the oxygen atom of each molecule that showed up when photographed using the microscope. With this method, it is said that one bit of data can be stored in just 12 atoms, compared to about one million atoms that was used before.

***A Boy and His Atom* is the world's smallest movie. You would probably be interested to know how it is possible to make such a movie. But first, let's find out more about atoms!**

19.1 The atom

In this section, you will learn the following:
- Describe the structure of an atom.
- Know how atoms form positive or negative ions.
- S Describe how the scattering of alpha (α-) particles by a sheet of thin metal provide evidence to support the nuclear model of the atom.

What is an atom?

In the kinetic particle model of matter, matter is modelled as being made up of particles. What are these particles? They are atoms, molecules, ions and electrons. In this chapter, you will learn about other particles and how they are related to atoms, ions and electrons.

LINK

Recall what you have learnt in Chapter 8 about the particles that make up matter.

An atom is the smallest unit of a chemical element. However, each atom is made up of even smaller particles. You have learnt about electrons, which carry negative charges. Electrons are many million times smaller than an atom. They are part of an atom.

An **atom** consists of a *positively charged nucleus and negatively charged electrons in orbit around the nucleus* (Figure 19.1). Strong attractive forces between the positively charged nucleus and negatively charged electrons hold the electrons to the atom. The electrons furthest from the nucleus could become detached by friction or by other means.

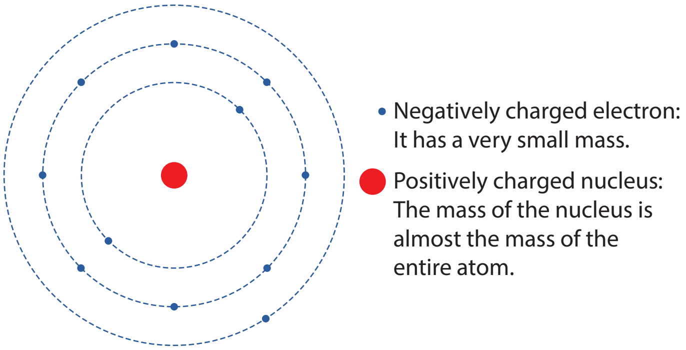


Figure 19.1 *Simplified structure of an atom*

How do atoms form ions?

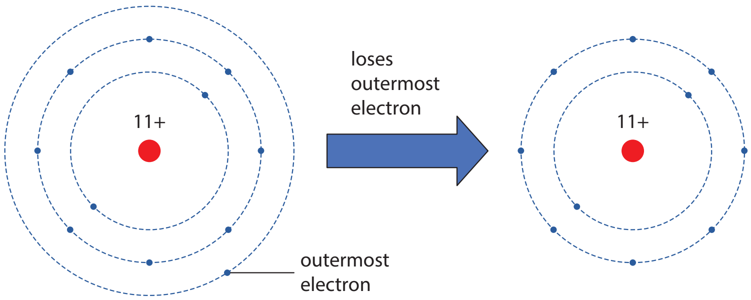
An electrically neutral atom has equal negative charges and positive charges. How many electrons are there in the atom in Figure 19.1? Each electron carries the same quantity of negative charge. How many positive electronic charges should be in the nucleus for it to be a neutral atom?

An atom which loses or gains electrons has unbalanced positive and negative charges.

An atom which *loses electrons* has more positive charges — it becomes a **positive ion**.

An atom which *gains electrons* has more negative charges — it becomes a **negative ion**.

Figure 19.2 shows how a positive ion is formed.



A neutral atom has equal number of positive and negative charges. In this atom, there are 11 electrons, so the nucleus has 11 positive charges.

A positive ion has more positive charges than negative charges. This ion has only 10 electrons, but its nucleus has 11 positive charges.

Figure 19.2 *When an atom loses electrons, it becomes a positive ion.*

Figure 19.3 shows how a negative ion is formed.

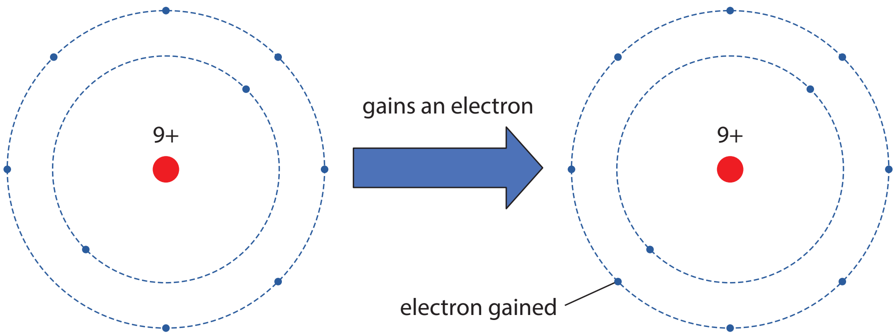


Figure 19.3 *When a neutral atom gains electrons, it becomes a negative ion.*

QUICK CHECK

Atom *A* is a neutral atom. It has 24 electrons. Its nucleus has the same number of positives charges.

True or false?

What evidence do we have to support the nuclear model of the atom?

In 1911, scientists Geiger and Marsden carried out an experiment to study the internal structure of atoms. They directed alpha (α-) particles from a radioactive source at a thin metal foil (Figure 19.4). This is like shooting bullets at a locked box to find out what sort of material is hidden inside — if the bullets are deflected instead of passing right through, the box must contain some very dense material.

LINK

A radioactive source emits radioactive particles such as find out more in Chapter 20.

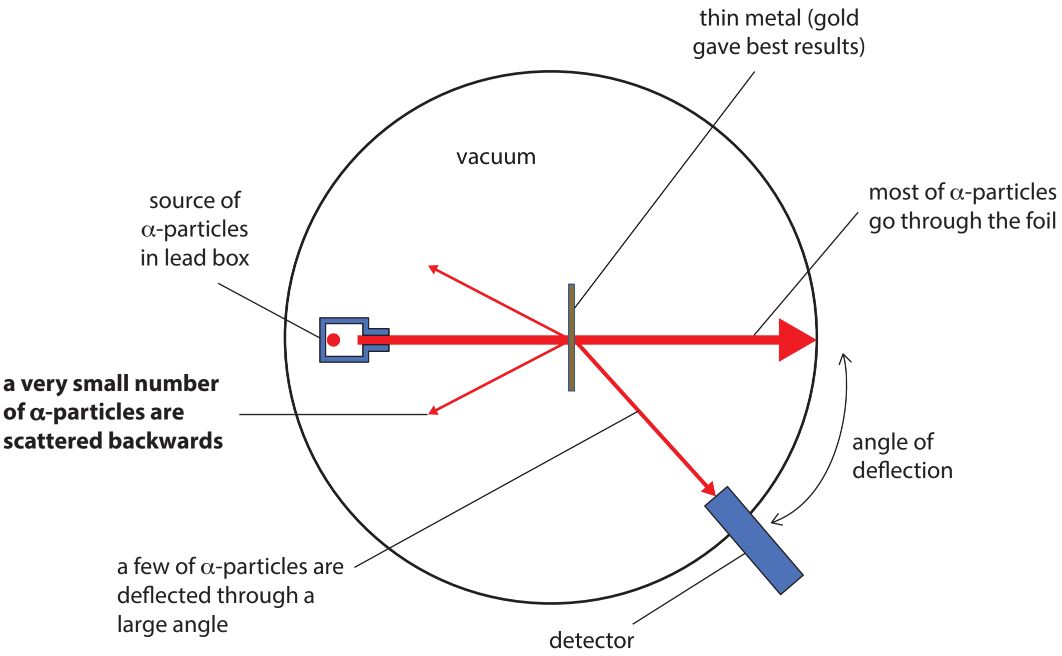


Figure 19.4 *Scattering of a-particles by thin metal foil*

ENRICHMENT INFO

Other Models of the Atom

The nuclear or planetary model of the atom (1911) by Ernest Rutherford was not the only model proposed to explain the atomic structure. Before this, there were the solid sphere model (1803) and the plum pudding model (1904).

Scientists continued to study atoms and later proposed the Bohr's model (1913) and the quantum model (1926) (Figure 19.6).

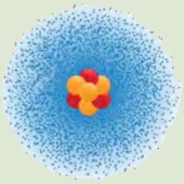


Figure 19.6 *The quantum atomic model suggests that electrons move in clouds around the nucleus instead of in fixed orbits.*

WORD ALERT

massive: has large mass

ENRICHMENT INFO

Work in groups. Search the Internet to find out more about the different models of the atom. Create a slide presentation and present your findings to the class.

LINK

Exercises 19A, pp. XX-XX

Geiger and Marsden's supervisor, Ernest Rutherford, was very puzzled by the fact that a few α-particles could be scattered backwards while almost all the particles passed right through. He knew that α-particles are positively charged particles. Also, the mass of an α-particle is much smaller than the mass of a gold atom.

Based on some mathematical calculations, Rutherford showed that the experimental results provided evidence for an atom that has

- a very small nucleus surrounded by mostly empty space (almost all the α-particles go right through);
- a nucleus containing most of the mass of the atom (an electron has a very small mass);
- a nucleus that is positively charged (positively charged α-particles are repelled).

The few α-particles that scattered backwards were going so close to the nucleus that they were strongly repelled as shown in Figure 19.5.

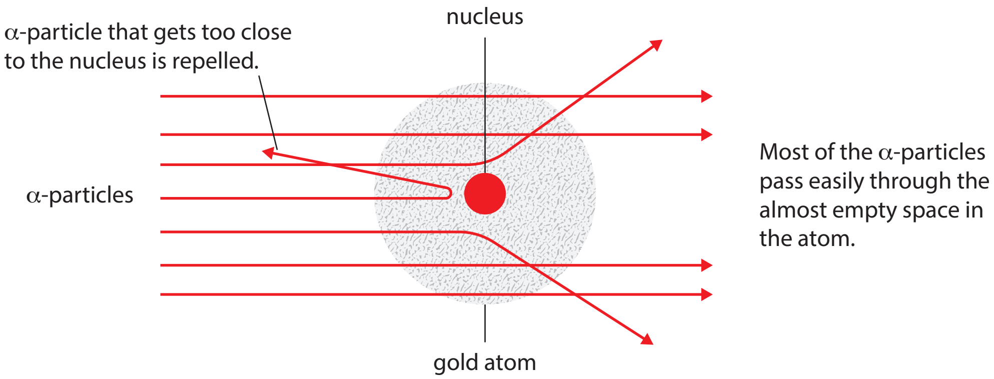


Figure 19.5 *Experimental evidence for a small, massive and positively charged nucleus surrounded by mostly empty space*

Let's Practise 19.1

1 Complete the sentences.

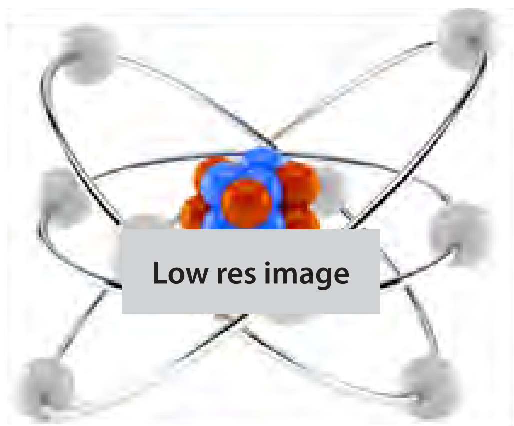
(a) An atom consists of a ____________ (positively/negatively) charged nucleus and ____________ (positively/negatively) charged electrons in orbit round the nucleus.

(b) When an atom ____________ (gains/loses) electrons, it becomes a positive ion.

(c) A negative ion is formed when an atom ____________.

2 The scattering of α-particles by a sheet of thin metal supports the nuclear model of the atom. What evidence about the nucleus does the experiment provide?

3 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.



19.2 The Nucleus

In this section, you will learn the following:

- Describe the composition of the nucleus in terms of protons and neutrons.
- State the relative charges of protons, neutrons and electrons.
- Define *proton number* (atomic number) Z and *nucleon number* (mass number) A.
- Calculate the number of neutrons in a nucleus.
- Use the nuclide notation $^{A}_{Z}X$.
- Explain the meaning of *isotope* and state that an element may have more than one isotope.

What makes up the nucleus of an atom?

Experiments show that the **nucleus** of an atom consists of two types of particles — **protons** (positively charged) and **neutrons** (no charge). Figure 19.7 shows the structure of a helium atom. The two protons are responsible for the nucleus being positively charged.

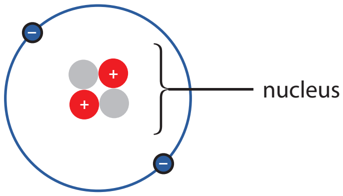


Figure 19.7 *The nucleus of a helium atom is made up of two protons and two neutrons.*

The amount of charge carried by each proton is the same as that carried by an electron. Can you recall the SI unit for charge? It is the coulomb. The charge of an electron is very much smaller than 1 coulomb. Instead of using the specific small number for the charge of an electron, scientists prefer to express the charge of small particles like electrons and protons in terms of the charge of an electron. Thus, the **relative charge of an electron is –1** (because it is negative) and the **relative charge of a proton is +1**. As the neutron does not carry any charge, the **relative charge of a neutron is 0**.

Proton number *Z*

The number of protons in an atom is called the **proton number** or atomic number. The symbol Z is used to represent the proton number of an element. It is unique to each element.

In a neutral atom, the total positive charge must equal the total negative charge. Therefore, in a neutral atom, the number of electrons is the same as the number of protons.

Nucleon number *A*

Protons and neutrons are also called *nucleons*. A nucleon can be a proton or a neutron. The total number of neutrons and protons in a nucleus is called the **nucleon number**. The symbol A is used to represent the nucleon number of the nucleus. (*Nucleon number* is also known as *mass number*.). Recall that the number of protons in a nucleus is the proton number Z. Therefore, we have:

The number of neutrons in a nucleus = nucleon number A – proton number Z

The nucleus of an atom is represented by the nuclide notation shown in Figure 19.8.

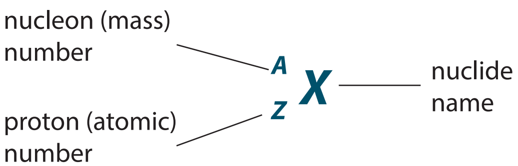


Figure 19.8 *Nuclide notation*

QUICK CHECK

A neutral atom with proton number Z has Z number of electrons.

True or false?

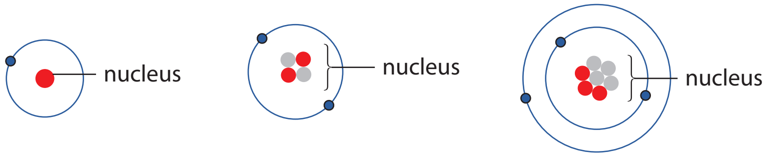
HELPFUL NOTES

Proton (atomic) number = number of protons in an atom

Nucleon (mass) number = total number of protons and neutrons in the nucleus

Figure 19.9 shows the structures of three atoms with different proton numbers. Take note of the number of electrons, protons and neutrons in each atom and their corresponding proton number *Z* and nucleon number *A*.

Key
- electron
- proton
- neutron



Nuclide notation	${}^{1}_{1}H$	${}^{4}_{2}He$	${}^{7}_{3}Li$
Atom	Hydrogen	Helium	Lithium
Number of electrons	1	2	3
Number of protons	1	2	3
Number of neutrons	0	2	4
Proton number *Z*	1	2	3
Nucleon number *A*	1	4	7

Figure 19.9 *Simplified atomic structures of the three lightest elements*

Worked Example 19A

The nucleus of an element is represented by ${}^{131}_{53}X$.

(a) How many electrons does the neutral atom contain?

(b) How many neutrons does the nucleus contain?

Solution

(a) The proton number $Z = 53$. So, the number of protons is 53.
In a neutral atom, the number of electrons must equal the number of protons. Hence, the number of electrons is 53.

(b) The nucleon number $A = 131$. So, the number of neutrons is $131 - 53 = 78$.

ENRICHMENT *THINK*

Figure 19.10 shows three isotopes of the element carbon.

1 Which isotope is the heaviest? Explain why.

2 Which isotope is the least stable? Explain why.

Isotopes

Isotopes of an element are the atoms that have the same number of protons but different number of neutrons in the nucleus.

Figure 19.10 shows the nuclide notation for three atoms of the same element carbon. How many electrons and protons does each atom have? How many neutrons does each atom have?

$${}^{12}_{6}C \qquad {}^{13}_{6}C \qquad {}^{14}_{6}C$$

Figure 19.10 *Isotopes of the same element have the same proton number but different nucleon numbers.*

The atoms have the same proton number, i.e., each atom has six protons. All atoms of the same element have the same number of protons. However, the number of neutrons is different for each atom. There are six neutrons in ${}^{12}_{6}C$, seven neutrons in ${}^{13}_{6}C$ and eight neutrons in ${}^{14}_{6}C$. The three atoms are *isotopes* of the same element.

Many elements have isotopes. An element may have more than one isotope. Carbon has three naturally occurring isotopes as shown in Figure 19.10. Hydrogen also has three naturally occurring isotopes, which include deuterium and tritium. Isotopes of the same element have identical chemical properties.

ENRICHMENT THINK

Why do you think isotopes of the same element have identical chemical properties?

Let's Practise 19.2

1 State the relative charge of
   (a) a proton;
   (b) a neutron;
   (c) an electron.

2 The following statement describes the nucleus of atom *X*.
   The proton number Z of atom X is 17. The nucleon number is 35.
   (a) State the meanings of the underlined terms.
   (b) Write down the nuclide notation for the nucleus of this atom.
   (c) How many neutrons are in the nucleus?
   (d) Atom *Y* has the same proton number 17, but its nucleon number is 37. Based on this information, how is *X* related to *Y*?

3 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK

Exercises 19B, pp. XX–XX

19.3 Nuclear Fission and Nuclear Fusion

In this section, you will learn the following:

- Describe the processes of *nuclear fission* and *nuclear fusion*. Include nuclide equations and mass and energy changes.
- Know the relationship between the proton number and the relative charge on a nucleus.
- Know the relationship between the nucleon number and the relative mass of a nucleus.

What is nuclear fission?

A neutron is a small particle that has no charge. It can get close to a positively charged atomic nucleus without being repelled by it. Scientists used neutrons to probe the nucleus of various elements. They carried out experiments similar to hitting a metal foil with α-particles but used neutrons instead.

The uranium-235 atom, ${}^{235}_{92}U$, has a big nucleus consisting of 235 nucleons. It has 92 protons and 143 (235 – 92) neutrons.

In 1938, scientists experimented with hitting uranium-235 with neutrons. The nucleus split into two almost equal parts and released more neutrons. A lot of energy was also released in the process. This splitting of the atomic nucleus is called *nuclear fission*.

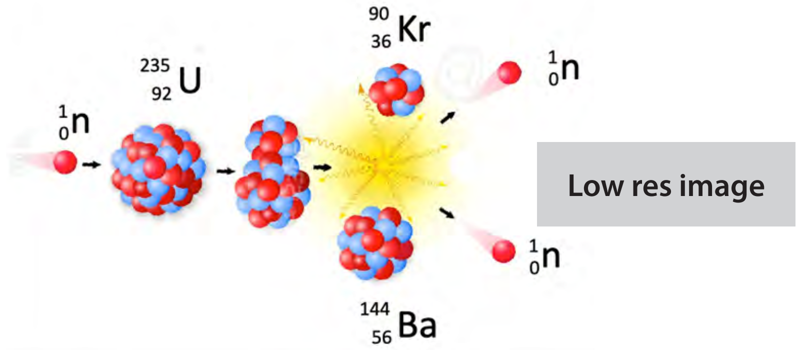
Nuclear fission is a process in which the nucleus of an atom splits (usually into two parts) and releases a huge amount of energy.

WORD ALERT

Probe: examine or investigate in detail

Fission: break up into parts

What happens to the split nucleus during a nuclear fission? The original atom becomes atoms of two different elements. This is a type of nuclear reaction. It can be represented by a nuclide equation as shown in Figure 19.11.



$$^{1}_{0}\mathbf{n} + ^{235}_{92}\mathbf{U} \rightarrow ^{144}_{56}\mathbf{Ba} + ^{90}_{30}\mathbf{Kr} + 2\,^{1}_{0}\mathbf{n} + \mathbf{energy}$$

Figure 19.11 *During a nuclear fission, a massive nucleus splits into smaller nuclei, releasing a huge amount of energy.*

In a nuclear reaction, *the total number of nucleons before and after the reaction is the same*. Add up the nucleon numbers on the left-hand side of the nuclide equation in Figure 19.11. It should equal the sum of the nucleon numbers on the right-hand side. The total number of nucleons before fission is 1 + 235 = 236. After fission, the total number of nucleons is 144 + 90 + 2(1) = 236.

The total relative charge before and after should also be the same.

What is the relative charge on the nucleus of an atom? Recall that the relative charge on each proton is +1. The relative charge on a neutron is 0. The proton number Z gives the number of protons in the nucleus.

The **relative charge on the nucleus** is the same as the proton number Z of the nucleus.

In Figure 19.11, the total relative charge before fission is 0 + (+92) = +92.

After fission, the total relative charge is 56 + (+36) + 2(0) = +92.

In a nuclear fission, there are a number of possible fission products. Therefore, there are a number of possible nuclide equations.

For example: $^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{139}_{56}\mathrm{Ba} + ^{94}_{36}\mathrm{Kr} + 3\,^{1}_{0}\mathrm{n}$ + energy

Check that the total number of nucleons and the total relative charge before and after the reaction are the same.

Worked Example 19B

In the following nuclide equation, what are the missing nucleon number A and proton number Z?

$^{233}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{137}_{54}\mathrm{Xe} + ^{A}_{Z}\mathrm{Sr} + 3^{1}_{0}\mathrm{n}$

Solution

Before fission, total nucleon number = 233 + 1 = 234

After fission, total nucleon number = 137 + A + 3(1) = 140 + A

Equating the total nucleon number before and after fission, 140 + A = 234

$\Rightarrow \therefore A = 94$

Before fission, total relative charge = (+92) + 0 = +92

After fission, total relative charge = (+54) + Z + 0 = (+54) + Z

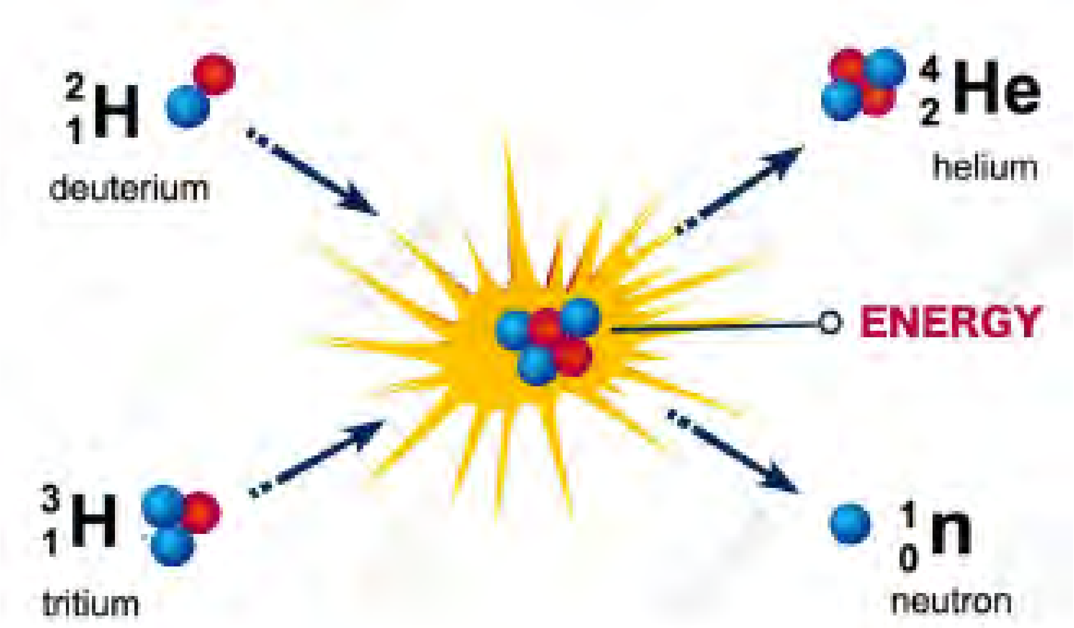
Equating the total relative charge before and after fission, 54 + Z = 92

$\Rightarrow \therefore Z = 38$

What is nuclear fusion?

Nuclear fusion is a process in which two light atomic nuclei combine to form one heavier atomic nucleus, releasing a huge amount of energy.

Figure 19.12 shows an example of a nuclear fusion reaction.



Low res image

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n + \text{energy}$$

Figure 19.12 *Two hydrogen isotopes combine to form a larger helium atom in a nuclear fusion reaction.*

Just like in nuclear fission, the total number of nucleons before and after the fusion is the same. The total charges before and after is also the same.

Where does nuclear energy come from?

Nuclear energy is potential energy stored in the nucleus. This energy is converted from mass.

Nuclear scientists use relative mass (in atomic mass units) instead of the kilogram to measure the mass of a nucleus because it is very small. By definition, the mass of the nucleus of the carbon-12 atom is 12 atomic mass units. There are 12 nucleons in the nucleus of the carbon-12 atom. So, the relative mass of each nucleon should be 1 atomic mass unit.

However, very precise measurements show that the relative mass of a neutron which is not in a nucleus is slightly larger than 1 atomic mass unit. Similarly, the relative mass of a proton which is not combined in a nucleus is slightly larger than 1 atomic mass unit. So the total mass of the 12 nucleons that make up the carbon-12 nucleus is actually slightly larger than the mass of the nucleus itself.

This fact is true of all nuclei — the total mass of the nucleons that make up a nucleus is slightly larger than the mass of the nucleus itself.

What happens to the missing mass? It is converted to the energy that holds the nucleons together. This is the potential energy stored in the nucleus. During a nuclear reaction (nuclear fission or nuclear fusion), the neutrons and protons rearrange to form new nuclei. As a result, there is a very small change in mass. A huge amount of energy is released as a result of mass–energy conversion.

WORD ALERT

Fusion: joining of individual parts to become one

QUICK CHECK

In both nuclear fission and nuclear fusion, the total number of nucleons before and after each process is the same.

True or false?

HELPFUL NOTES

The mass–energy conversion of a nuclear fission is governed by the famous Einstein equation: $E = mc^2$

WORD ALERT
Ejected: forced or thrown out

In a nuclear fission, the total mass of the products (new nuclei and ejected neutrons) is smaller than the total mass of the original nucleus and neutron that hit it. In forming fission products, a lot of energy is released from the total reduced mass. Nuclear power stations use nuclear fission to generate energy (Figure 19.13).

Similarly, in nuclear fusion, the total mass of the two light nuclei before the fusion is more than the total mass of the heavier nucleus and the ejected neutron. The difference in mass is converted to energy released in the fusion process.

However, nuclear fusion is harder to achieve. The nucleus of an atom is positively charged. Like charges repel. In order for two positively charged nuclei to combine, they must overcome the strong repulsive force. Nuclear fusion takes place naturally at very high temperatures and pressures in the Sun. Unfortunately, nuclear fusion has only been used destructively in the hydrogen bomb (Figure 19.14). Scientists are trying to build nuclear fusion reactors that can be safely used.

Table 19.1 summarises the particles represented by $^{A}_{Z}X$.

Figure 19.13 *A nuclear power plant harnesses the energy released from nuclear fission.*

Table 19.1 *Summary of atomic particles*

Particle	Charge (relative charge)	Approximate mass (atomic mass unit)	Number of particles in nucleus
Proton	+1	1	Z
Neutron	0	1	$A-Z$
Electron	–1	$\frac{1}{2000}$	Z
Nucleus	$+Z$	A	

PHYSICS WATCH
Scan this page to watch a clip about the need to use nuclear energy responsibly.

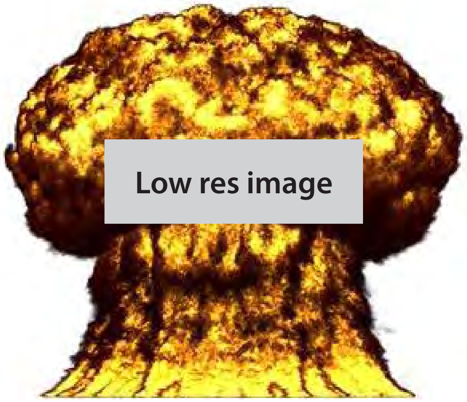


Figure 19.14 *The hydrogen bomb releases a huge amount of energy from nuclear fusion.*

Let's Practise 19.3

1 Table 19.2 compares two nuclide equations. Complete the table with suitable words from the list below.

nuclear fusion, nuclear fission, mass, number of nucleons, energy, charges, heavy nucleus split into lighter nuclei, lighter nuclei combine to form heavier nucleus

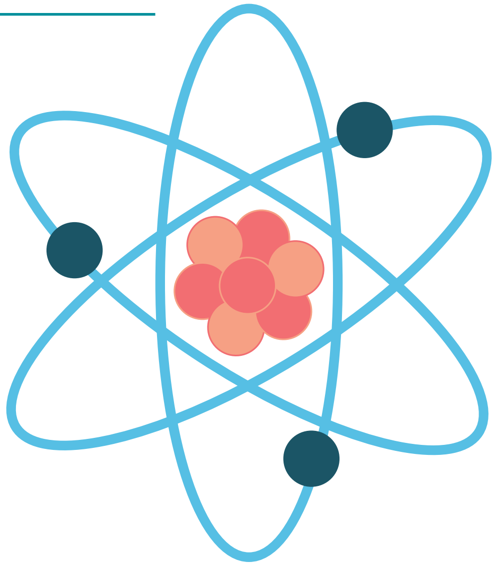
You may use some words more than once. The first has been done for you.

Nuclide equation	$^{239}_{94}Pu + ^{1}_{0}n \rightarrow ^{137}_{54}Xe + ^{103}_{40}Zr + ^{1}_{0}n$	$^{2}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{2}He + ^{1}_{0}n$
Description of process	Heavy nucleus split into lighter nuclei	
Name of process		
Total ________ before	240	4
Total ________ after	240	4
Total ________ before	+94	+2
Total ________ after	+94	+2
Total ________ before compared to after	greater and so ________ released	greater and so ________ released

2 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB
Exercises 19C–19D, pp. XX–XX
Exercise19E Let's Reflect, p. X

Let's Map It



Geiger and Marsden experiment (Rutherford's scattering)

provides insights into

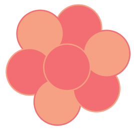
THE NUCLEAR ATOM

can

consists of

Negatively charged electrons

Positively charged nucleus

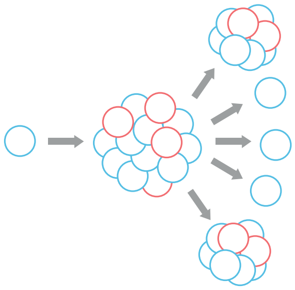


contains

Nucleons
- 2 types of particles, protons and neutrons
- Nucleon number A

Protons
- Positively charged
- Proton number Z

Neutrons
- No charge
- Number of neutrons (A-Z)



Nuclide notation

$${}^{A}_{Z}X$$

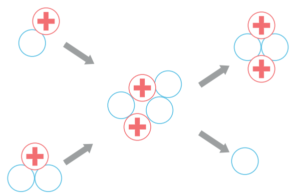
- Element X
- Nucleus has Z protons and $A - Z$ neutrons

used to represent

Isotopes of elements
- Same proton number Z
- Different nucleon number A

used in nuclide equations to describe the

Nuclear processes of
- Nuclear fission
- Nuclear fusion



Let's Review

Section A: Multiple-choice Questions

1 Which of the following statements correctly describe the structure of an atom?

A An atom consists of positively charged protons and negatively charged electrons tightly bound together.

B An atom consists of positively charged protons and negatively charged neutrons tightly bound together.

C An atom consists of a positively charged nucleus and negatively charged electrons in orbit around the nucleus.

D An atom consists of a positively charged nucleus and negatively charged neutrons in orbit around the nucleus.

2 How does a neutral atom become a positive ion?

A It gains protons. **B** It loses protons.

C It gains electrons. **D** It loses electrons.

3 S The scattering of α-particles by thin metal provides evidence for

A a nucleus consisting of protons and neutrons.

B a nucleus that is charged.

C electrons carrying negative charges.

D neutrons not carrying any charge.

4 An atom has proton number $Z = 19$ and nucleon number $A = 40$. Which of the following rows describes the composition of the neutral atom?

	Number of protons	*Number of electrons*	*Number of neutrons*
A	40	40	19
B	19	21	40
C	40	21	19
D	19	19	21

5 Which of the following nuclides has equal number of neutrons and protons?

A ${}^{1}_{1}\text{H}$ **B** ${}^{6}_{3}\text{Li}$

C ${}^{10}_{4}\text{Be}$ **D** ${}^{17}_{8}\text{O}$

6 Which pairs of nuclides are isotopes?

A ${}^{35}_{17}X$ and ${}^{37}_{17}Y$ **B** ${}^{35}_{17}X$ and ${}^{79}_{35}Y$

C ${}^{37}_{17}X$ and ${}^{37}_{20}Y$ **D** ${}^{79}_{35}X$ and ${}^{81}_{37}Y$

Section B: Short-answer and Structured Questions

1 The nuclide notation for an atom is ${}^{14}_{7}\text{N}$.

(a) What does the number 14 represent?

(b) What does the number 7 represent?

(c) The nuclide notation for another atom of the same element is ${}^{15}_{7}\text{N}$. Explain how the two atoms can be of the same element.

2 Figure 19.15 shows the structures of two atoms *X* and *Y*. One of the atoms is not a neutral atom.

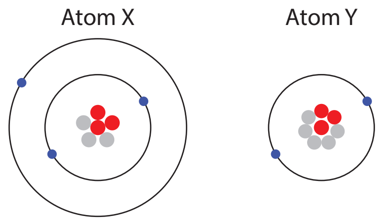


Figure 19.15

(a) Complete the key to the Figure 19.14.

● electron

● ____________________

● ____________________

(b) Which atom is neutral?

Give the nuclide notation for this atom.

(c) Explain why the atoms in Figure 19.8 belong to the same element.

3 S In a nuclear reactor, an atom of uranium-235 undergoes nuclear fission.

(a) Explain what is meant by *nuclear fission*.

(b) Describe how energy is produced by the fission of an atom of uranium-235.

4 S A nuclear reaction is represented by the following nuclide equation:

${}^{1}_{1}\text{H} + {}^{2}_{1}\text{H} \rightarrow {}^{3}_{2}\text{He} + \text{energy}$

(a) Explain the type of process represented by the nuclide equation.

(b) Energy is released by the process. Describe the changes that result in energy being released.

CHAPTER

20 Radioactivity

PHYSICS WATCH

Scan this page to watch a clip about radioactive exposure.

QUESTIONS

- What is the nature of the radiation that pilots are trying to avoid?
- Where do you think the radiation comes from?
- How does following the advice helps pilots?

Toshiro, a Japanese pilot, spends a lot of time in the sky at altitudes between 6000 to 12000 metres. He has clocked up to 1000flight hours per year for the past 12 years. That's more than 10 000 flight hours! Before this, Toshiro used to clock up to 1650 flight hours per year.

Pilots are being advised to reduce the amount of working time spent on long flights and flights that are at high altitudes. They are even told not to fly frequently over the two poles — the North Pole and the South Pole!

What are they trying to avoid?

Radiation!

20.1 Detection of Radioactivity

In this section, you will learn the following:
- Know what is meant by *background radiation*.
- Know the sources that make a significant contribution to background radiation, including radon gas (in the air), rocks and buildings, food and drink and cosmic rays.
- Know that ionising nuclear radiation can be measured using a detector connected to a counter.
- Use count rate measured in counts/s or counts/min.
- S Use measurements of background radiation to determine a corrected count rate.

What is background radiation?

Radiation is all around us. We are commonly exposed to electromagnetic radiation. Examples are visible light and infrared light from the Sun, and microwaves from mobile phones. These are non-ionising radiation. There are also other types of radiation which are ionising.

Lonising radiation is radiation with high energies that can *knock off electrons from atoms to form ions*. Very high frequency ultraviolet, X-rays and gamma rays are examples of ionising electromagnetic radiation. High-energy particles from cosmic rays and from naturally occurring radioactive materials are examples of ionising nuclear radiation.

Background radiation is *ionising nuclear radiation* in the environment when no radioactive source is deliberately introduced. Sources of background radiation can be natural or artificial (Table 20.1).

ENRICHMENT *INFO*

Cosmic Rays

Cosmic rays come from the Sun and other space objects outside the Solar System, such as distant galaxies. They are not like light rays. They consist mainly of protons and a small percentage of other subatomic particles.

The Earth's atmosphere reduces most of the energy of cosmic rays. When cosmic rays collide with the Earth's atmosphere, less energetic particles are created. At ground level, exposure to cosmic rays is much less than at higher levels above sea levels.

Table 20.1 *Sources of background radiation*

Natural sources	Artificial sources
• Rocks • Radon gas in the air • Food and drink (e.g. foods high in potassium such as banana contain small amounts of radioactive potassium-40) • Cosmic rays	• Medical X-rays • Building materials • Waste products from nuclear power stations

Natural sources make a significant contribution to background radiation. At ground level, the amounts of background radiation are usually well below the levels that the human body can tolerate.

Figure 20.1 *The people in the photos are exposed to background radiation. For each situation, can you identify the sources of the background radiation?*

How do we measure ionising nuclear radiation?

Ionising nuclear radiation can be measured using a detector connected to a counter (Figure 20.2).

To measure the background radiation, follow these steps:

1. Remove all known radioactive sources and set the counter to zero.
2. Start the counter and a stopwatch.
3. Stop the counter after 10 minutes and record the number of counts.
4. Divide the number of counts by 10 to obtain the number of counts per minute.
5. Repeat your measurement at least once to obtain an average value.

Alternatively, record the number of counts for a longer time interval, for example, 20 minutes.

The background count rate is measured in **counts per minute (counts/min)**. When the count rate is high, the counts are measured for a shorter time, for example, 30 seconds. The average count rate in such a case is measured in counts per second (counts/s).

S When carrying out any measurements with radioactive sources, you should first measure the background radiation. Subtract this background count rate from your measurements to obtain the corrected count rate for the radioactive source.

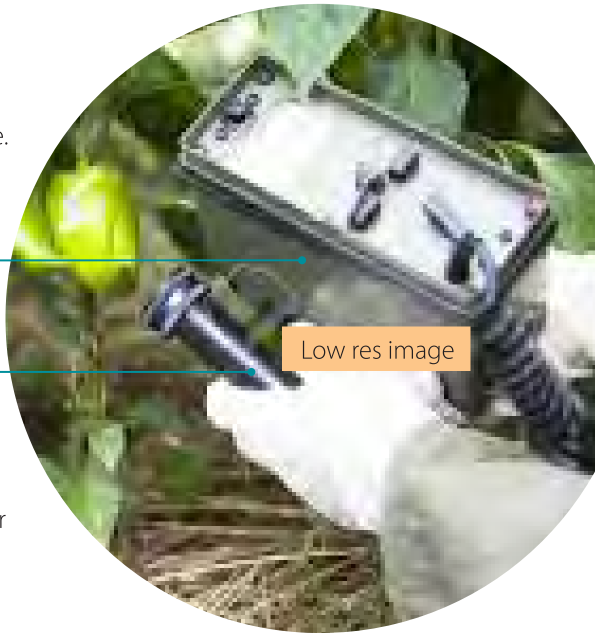


Figure 20.2 A detector attached to a counter is used to measure ionising nuclear radiation.

Worked Example 20A

(a) A teacher turned on a radiation detector and observed the number of counts at 10-minute intervals. She recorded her observations as follows: 198, 180, 175, 200. Determine the average background count rate.

(b) Next, the teacher carefully placed the detector in front of a radioactive source. She measured the number of counts for 30 seconds. It was 1243. Calculate the count rate for the radioactive source in counts/s.

(c) S What was the corrected count rate for the radioactive source in counts/min?

Solution

(a) Average number of counts for 10 minutes $= \frac{198 + 180 + 175 + 200}{4} = 188$

Average background count rate $= \frac{188}{10} = 19$ counts/min

(b) Count rate of the radioactive source $= \frac{1243}{30} = 41$ counts/s

(c) S Count rate of radioactive source $= \frac{1243}{0.5} = 2486$ counts/min (30 s = 0.5 min)

Corrected count rate = 2486 – 19 = 2467 counts/min

QUICK CHECK

When measuring ionising nuclear radiation from a radioactive source, the counter will give the true count rate.

True/false?

Let's Practise 20.1

1 What is background radiation?
2 Name **two** natural sources of background radiation.
3 A student turned on a radiation detector for 20 minutes. The counter showed a count of 420. What was the background radiation?
4 S In an experiment, the number of counts from a radioactive source was measured for five minutes. It was 120. The background count was 20 counts/min. What was the corrected count rate for the radiation from the radioactive source?
5 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

Exercise 20A, pp. XX–XX

20.2 Nuclear Emission

In this section, you will learn the following:

- Describe the emission of radiation from a nucleus as spontaneous and random in direction.
- Identify alpha (α-), beta (β-) and gamma (γ-) emissions from the nucleus by recalling their nature, their relative ionising effects and their relative penetrating abilities.
- S Describe the deflection of α-particles, β-particles and γ-radiation in electric fields and magnetic fields.
- S Explain their relative ionising effects with reference to kinetic energy and electric charge.

How is radiation emitted from a nucleus?

If you measure background radiation at one-minute intervals, you will observe that the count rate is always different for successive minutes. This is not because of errors in counting. The count rate will always be different. Why is this so?

The radiation emitted by a radioactive nucleus is *spontaneous* and *random in direction*. It is not possible to make the radioactive nucleus emit radiation by heating, cooling, chemical means or any other method. There is no way to predict when a radioactive nucleus will emit radiation. It is also impossible to know the direction in which the emitted radiation will leave a nucleus. This is why we need to make measurements over a sufficiently long period of time to obtain an average count rate.

WORD ALERT A-Z

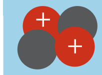
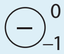
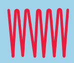
Spontaneous: happening suddenly

Figure 20.3 *How does popping popcorn simulate radioactive emission?*

What are the three types of nuclear emission?

There are three types of nuclear emission: *alpha (α-) particles, beta (β-) particles* and *gamma (γ-) rays*. Their properties are shown in Table 20.2.

Table 20.2 *The three types of nuclear emission*

Nuclear emission	Nature	Relative ionising effect	Relative penetrating ability
α-particles  ${}^{4}_{2}\alpha$	An **α-particle** consists of two protons and two neutrons tightly bound together without any orbiting electrons. It is identical to a *helium nucleus*.	Highest	• Least • They are easily absorbed by a piece of paper, a thin aluminium foil or human skin.
β-particles  ${}^{0}_{-1}\beta$	A **β-particle** is a fast-moving *electron* ejected from a radioactive nucleus.	Medium	• Medium • They are absorbed by a few-mm-thick aluminium.
γ-rays 	A **γ-ray** is electromagnetic radiation emitted by a nucleus with excess energy.	Least	• Highest • They pass through most materials easily and are absorbed by a few-cm-thick lead or very thick concrete.

Worked Example 20B

An experiment was set up to investigate the penetrating power of radiation from a radioactive source (Figure 20.4).

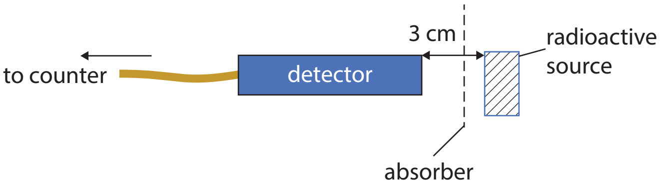


Figure 20.4

Table 20.3 shows the results.

Table 20.3

Background count	25 counts per minute
Count with source only	4200 counts per minute
Count with source and paper absorber	4180 counts per minute
Count with source and 3-mm-thick aluminium absorber	1200 counts per minute

What type or types of radiation does the radioactive source emit?

Solution

No α-particles are emitted because the count rate with the paper absorber is about the same as without any absorber. The emission is partially absorbed by the 3-mm-thick aluminium — so this must be the β-particles. Some emission is not absorbed because the count rate is quite high at 1200 counts per minute while the background count is only 25 counts per minute. This must be due to γ-emission from the source. The radioactive source emits β-particles and γ-rays.

Relative ionising effects of nuclear emission

An ion is formed from a neutral atom when an electron leaves the atom. Energy has to be transferred to the electron for it to leave the atom.

α- and β-particles are fast-moving charged particles. They have large amounts of kinetic energy. α-particles have a bigger amount of kinetic energy than β-particles. Therefore, they have a bigger ionising effect.

There is electrical force between the moving charged particles and the charged electrons in the atoms. The electrical force transfers energy to the electrons in the atom from the kinetic energy of the moving particles. The bigger the force, the more energy can be transferred. Table 20.3 shows that an α-particle has twice the amount of charge of a β-particle. It has a bigger force than a β-particle. Thus, α-particles form more ions within a short distance than β-particles.

Table 20.4 *Relative charges and mass of nuclear emission*

Nuclear emission	Relative charge	Mass (atomic mass units)
α-particles	+2	4
β-particles	–1	$\frac{1}{2000}$
γ-rays	0	0

γ-rays are electromagnetic waves. They do not have any charge or mass. They transfer nuclear energy from the radioactive nuclei. γ-rays have the least ionising effect. α-particles have the greatest ionising effect because of its +2 relative charge and high amount of kinetic energy.

What happens when α-particles, β-particles and γ-rays travel through an electric field?

Figure 20.5 shows three different sources of nuclear radiation in a strong electric field. The path of each type of nuclear radiation is deflected differently. Can you identify the type of nuclear radiation? (Hint: What type of charge is carried by each type of nuclear radiation?)

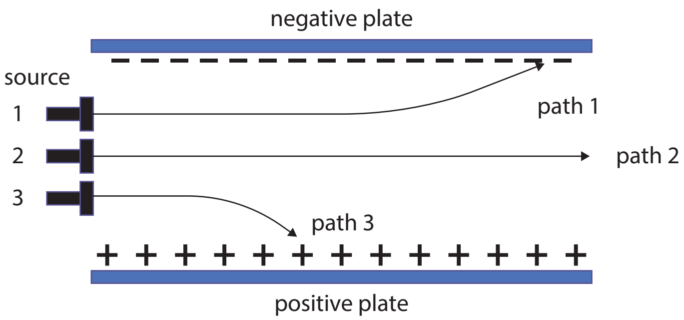


Figure 20.5 *Nuclear radiation passing through an electric field*

Source 1 emits α-particles. The positively charged particles are attracted to the negative plate (path 1). The deflection is not as much as path 3 because they have a relatively big mass.

Source 3 emits β-particles. The negatively charged electrons are attracted towards the positive plate (path 3). The deflection is more because they have a small mass.

Source 2 emits γ-rays which are not deflected (path 2) because they are electromagnetic waves.

What happens when α-particles, β-particles and γ-rays travel through a magnetic field?

Figure 20.6 shows the paths of three different types of nuclear radiation in a magnetic field. The magnetic field is coming out of the page. (The dots represent the pointed end of arrows coming out of the page.) Can you identify the types of nuclear radiation? (Hint: determine the direction of the force on a stream of charged particles in a magnetic field.)

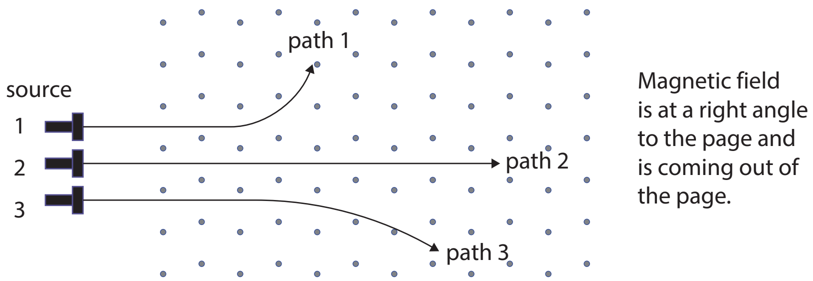


Figure 20.6 *Nuclear radiation passing through a magnetic field*

Source 2 emits γ-rays which are not deflected by the magnetic field because they do not carry any charge.

Source 1 emits β-particles. The particles are deflected upwards since they are negatively charged. They are deflected more than the alpha particles in path 3 because they have smaller mass.

Source 3 emits α-particles which are deflected downwards and less than the particles in path 1.

Let's Practise 20.2

1 A student was trying to measure the radiation from a radioactive source. He took readings for a short time. His readings were as follows:

Counts/s: 520 530 510 515 540

The student suggested that the counter was faulty because the readings kept changing. What explanation can you give for the changing count rate?

2 Draw lines to match the type of nuclear radiation (A) to the correct nature (B), relative ionising effect (C) and relative penetrating abilities (D):

A	B	C	D
α	Electromagnetic radiation	Least ionising	Most penetrating
β	Negatively charged small particles	Most ionising	Medium penetrating
γ	Positively charged particles with high kinetic energy	Medium ionising	Least penetrating

3 **(a)** S The radiation from a radioactive source is not deflected in an electric field or in a magnetic field. What is this radiation?

(b) What type or types of nuclear emission will be defected in an electric field and in a magnetic field? How can you verify the type of emission by observing its deflection?

4 S What two properties of α-particles explain their strong ionising effect?

5 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB
Exercise 20B, pp. XX–XX

20.3 Radioactive Decay

In this section, you will learn the following:

- Know what is meant by *radioactive decay* and that the changes involved are spontaneous and random.
- State that what happens to the nucleus during α-decay or β-decay.
- S Know why isotopes of an element may be radioactive.
- S Describe the effect of α-decay, β-decay and γ-emissions on the nucleus.
- S Use decay equations, using nuclide notation, to show the emission of α-particles, β-particles and γ-radiation.

What is radioactive decay?

Radioactive sources contain *unstable* nuclei. These nuclei are unstable because they change spontaneously and randomly.

A change in an unstable nucleus can result in the emission of α-particles or β-particles and/or γ-radiation. This nuclear process is called **radioactive decay**.

It is impossible to predict which nucleus or when a particular nucleus will decay because radioactive decay is *spontaneous and random*. However, all nuclei of the same isotope will emit the same type of nuclear radiation.

- When a nucleus undergoes **α-decay**, it emits an *α-particle*.
- When a nucleus undergoes **β-decay**, it emits a *β-particle*.

During α- or β-decay, the nucleus changes to that of a different element.

WORD ALERT A-Z

Nuclei: plural of nucleus

Decay: break down into smaller parts

Why are some isotopes radioactive?

The nuclei of some isotopes like uranium($^{238}_{92}U$) and caesium ($^{137}_{55}Cs$) are very **massive**. Such a massive nuclide has more than a hundred nucleons packed in its nucleus. These nuclei tend to be unstable. They can change into lighter nuclei by emitting α-particles.

The element carbon has three natural isotopes: $^{12}_{6}C$, $^{13}_{6}C$ and $^{14}_{6}C$. Which nuclide has the most neutrons? By looking at the nucleon number, we know it is carbon-14. Carbon-14 has eight neutrons, which is more than the six protons in the nucleus. Similarly, the nuclide sodium-24 ($^{24}_{11}Na$) has 13 neutrons but only 11 protons. These nuclides with excess neutrons are unstable. They can change into nuclei with fewer excess neutrons by emitting β-particles.

> **WORD ALERT**
>
> **Massive:** has large mass

How does α-decay make a nucleus more stable?

When a very massive nuclide such as radon-224 decays by emitting an α-particle, it changes into a nucleus of a lighter element. This nucleus has a nucleon number *A* smaller by 4 and proton number *Z* smaller by 2. The new element formed is polonium. How does this happen? The nuclide equation below shows how radon-224 undergoes α-decay:

nucleon number decreases by 4

$$^{222}_{86}Rn \rightarrow \, ^{218}_{84}Po + \, ^{4}_{2}He$$

proton number decreases by 4

During α-decay, the nucleus ejects four nucleons consisting of two protons and two neutrons. The nucleus now has four fewer nucleons. The four ejected nucleons form a helium nucleus. This helium nucleus is referred to as an α-particle and can simply be written as $^{4}_{2}\alpha$. The decay equation can then be written as:

$$^{222}_{86}Rn \rightarrow \, ^{218}_{84}Po + \, ^{4}_{2}\alpha$$

Although polonium is less massive than radon, it is still not stable. It further decays by emitting α-particles to become the lead nuclide $^{214}_{82}Pb$.

> **QUICK CHECK**
>
> The nuclide equation for α-particle decay of polonium is as follows:
>
> $^{218}_{84}Po \rightarrow \, ^{214}_{82}Pb + \, ^{4}_{2}\alpha$
>
> True or false?

How does β-decay make a nucleus more stable?

A β-particle is a negatively charged electron. However, there are no electrons in the nucleus of an atom. So how can a nucleus emit an electron?

The process is complex and involves another extremely small particle. To simplify, the following describes what happens during a β-decay:

- A neutron changes into a proton and an electron (neutron → proton + electron).
- The proton remains in the nucleus. The electron is emitted as a β-particle.
- As a result, *the proton number Z increases by one* while the *nucleon number A remains the same*.

As an example, let's take a look at carbon-14 undergoing β-decay as shown below:

nucleon number remains the same

$$^{14}_{6}C \rightarrow \, ^{14}_{7}N + \, ^{0}_{-1}\beta$$

proton number increases by 1

S

When carbon-14 emits a β-particle, it changes into the nitrogen nuclide with seven neutrons and seven protons. Before the decay, the carbon nuclide has eight neutrons but only six protons. The new nitrogen nuclide does not have excess neutrons compared to the number of protons.

The lead nuclide $^{214}_{82}\text{Pb}$ decays by β-emission to form the nuclide bismuth $^{214}_{83}\text{Bi}$. Try writing out the nuclide equation for this decay. Check your answer in the following discussion on γ-emission.

How does γ-emission make a nucleus more stable?

After a nucleus emits an α- or a β-particle, the nucleus may have excess energy. It releases this excess energy by emitting γ-rays. For example, when the lead nuclide $^{214}_{82}\text{Pb}$ decays, the nuclide, bismuth $^{214}_{83}\text{Bi}$ is left with excess energy. This excess energy is released as γ-emission. Both the number of protons and the number of neutrons in the nucleus are not changed in the process. During γ- emission, the proton number *Z* and the nucleon number *A* remain the same.

The two types of emission can be represented by the following nuclide equations:

$$^{214}_{82}\text{Pb} \rightarrow \, ^{214}_{83}\text{Bi}^* + \, ^{0}_{-1}\beta$$

$$^{214}_{83}\text{Bi}^* \rightarrow \, ^{214}_{83}\text{Bi} + \gamma$$

The asterisk * is used to indicate that a particular nucleus has excess energy (or is in an excited state). The equations are usually combined into one:

$$^{214}_{82}\text{Pb} \rightarrow \, ^{214}_{83}\text{Bi} + \, ^{0}_{-1}\beta + \gamma$$

Similarly, when radium decays to radon, the radon nucleus is left with excess energy, which it releases as γ-radiation:

$$^{226}_{88}\text{Ra} \rightarrow \, ^{222}_{86}\text{Rn} + \, ^{4}_{2}\alpha + \gamma$$

There are some rare artificial isotopes that emit only γ-rays, like the unstable technetium-99m. (The 'm' stands for 'metastable'.)

$$^{99m}_{43}\text{Tc} \rightarrow \, ^{99}_{43}\text{Tc} + \gamma$$

Table 20.5 summarises the changes to the nucleus during radioactive decay.

Table 20.5 *What happens to the nucleus during radioactive decay*

Type	Effect on nucleus	Decay equation
α-decay	• Loses two neutrons and two protons • Becomes a less massive nucleus of a different element	$^{A}_{Z}X \rightarrow \, ^{A-4}_{Z-2}Y + \, ^{4}_{2}\alpha$
β-decay	• One neutron in nucleus changes into a proton and an electron; proton remains in the nucleus, electron is emitted (β-particle) • Becomes the nucleus of a different element with fewer excess neutrons	$^{A}_{Z}X \rightarrow \, ^{A}_{Z+1}Y + \, ^{0}_{-1}\beta$
γ-emission	• Releases excess energy • No change in atomic number or mass number	$^{A}_{Z}X \rightarrow \, ^{A}_{Z}X + \gamma$ or $^{A}_{Z}X^* \rightarrow \, ^{A}_{Z}X + \gamma$

Let's Practise 20.3

1 Complete the sentences:

(a) ______________ is a change in an unstable nucleus that can result in the emission of α-particles or β-particles and/or γ-radiation. These changes are ______________ and ______________.

(b) During α- or β-decay, the nucleus changes to that of a different ______________.

2 S What two types of isotopes may be radioactive?

3 S Complete the sentences:

(a) When a nucleus emits an α-particle, its nucleon number ______________ and its proton number ______________.

(b) When a nucleus emits a β-particle, its nucleon number ______________ and its proton number ______________. It now has ______________ excess neutrons.

4 S Write the nuclide equations for the following two processes:

(a) $^{238}_{92}U$ decays to Th by emitting an α-particle and γ-radiation.

(b) $^{137}_{55}Cs$ decays to Ba by emitting a β-particle and γ-radiation.

5 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK

Exercise 20C, pp. XX–XX

20.4 Half-life

In this section, you will learn the following:

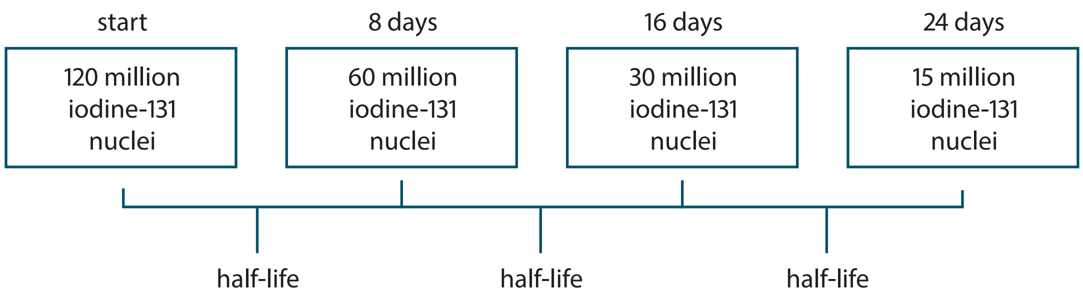
- Define the half-life of a particular isotope.
- Recall and use the definition of half-life in simple calculations.
- S Calculate half-life from data or decay curves from which background radiation has not been subtracted.
- S Explain how the type of radiation emitted and the half-life of an isotope determine which isotope is used for applications.

What is half-life?

Nobody knows exactly when a particular nucleus will decay. However, every isotope has a definite rate of decay which cannot be changed by heating, cooling or any other methods. We can make predictions about the decay of a large number of nuclei of a particular isotope because it has a fixed *half-life*.

The **half-life** of a radioactive isotope is the time taken for half the nuclei of that isotope in any sample to decay.

For example, the half-life of iodine-131 is eight days. Suppose there are 120 million iodine-131 in the beginning. Observe the number after 8 days, 16 days and 24 days. The results are as shown:



HELPFUL NOTES

The half-life of an isotope can also be understood as the time taken for the count rate of the radioactive emission to fall by half.

Experimentally, the time taken for the count rate of the radioactive emission to fall by half is the half-life of the isotope. The graph of count rate against time is called the **decay curve** (Figure 20.7).

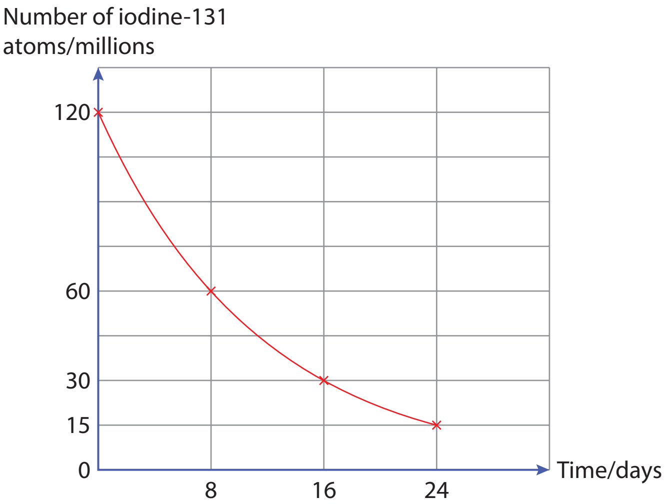


Figure 20.7 *Decay curve*

ENRICHMENT *THINK*

Technetium 99 has a half-life of 215 000 years. Its isomer, Technetium 99m, has a half-life of six hours.

Which of the two is suitable to be used as a medical tracer for scanning the internal organ of a patient? Explain why.

Worked Example 20C

In an experiment, a radiation detector was placed close to a radioactive source. The count rate was measured at five-minute intervals for 30 min. The results for the first 20 min are shown in Table 20.6.

Table 20.6

Time/min	0	5	10	15	20
Count rate Counts / min	12 012	8558	6098	4344	3095

(a) Use the data to estimate the half-life of the radioactive source.

(b) What could be the approximate count rate at the end of 30 min?

Solution

(a) At the start of the experiment, the count rate was 12 012 counts/min. Half of this rate is about 6000 counts/min. From the table, the count rate decreases to 6098 counts/min after 10 min. Therefore, the half-life of the radioactive source is about 10 min.

(You can check to see that after another 10 min (i.e. time = 20 min), the count rate is further halved from about 6000 to 3000 counts/min.)

(b) The half-life is 10 min. At the end of 20 min, the count rate was about 3000 counts/min. So, in the next 10 minutes (i.e. at the end of 30 min), this rate would be halved to 1500 counts/min.

Worked Example 20D

The decay curve of a radioactive isotope is shown in Figure 20.8. Use the graph to estimate the half-life of the isotope.

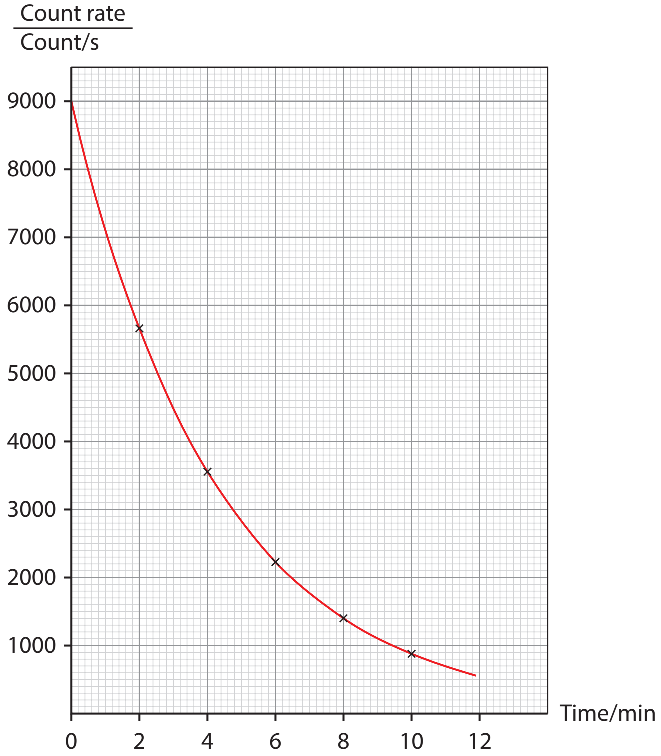


Figure 20.8 *Decay curve for a radioactive isotope*

Solution

The solution is shown in Figure 20.9 From the decay curve, the half-life is 3 min.

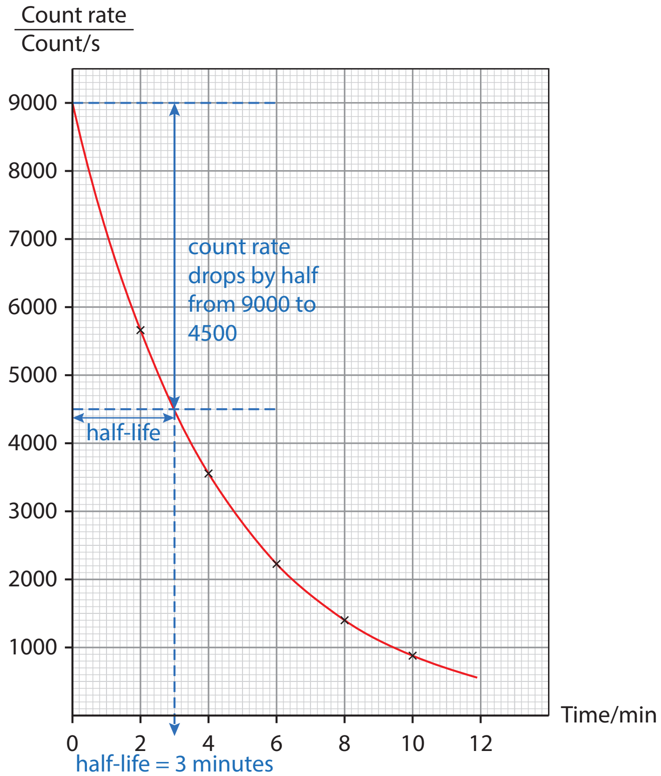


Figure 20.9 *Determining the half-life of an isotope from a decay curve*

In Worked Examples 20C and 20D, the count rates are very high. Now consider the decay curve in Figure 20.10. Why does the count rate remain at about 20 counts/min after some time?

The almost constant count rate of 20 counts/min is due to the background radiation. In this example, the small sample has completely decayed. What is the half-life of this isotope? From the decay curve in Figure 20.11, the half-life is 20 min.

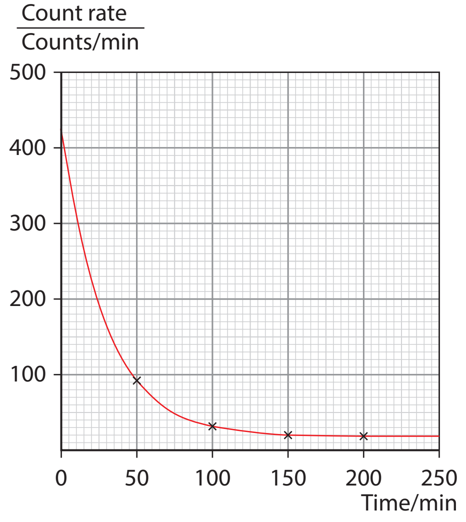


***Figure 20.10** Decay curve from which background radiation has not been subtracted*

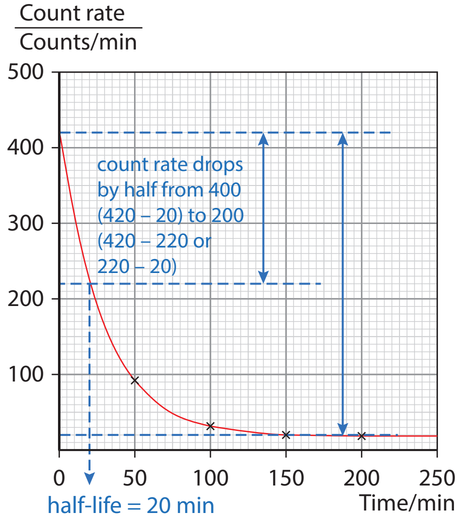


***Figure 20.11** Determining the half-life from decay curve from which background radiation has not been subtracted*

Worked Example 20E

In an experiment to measure the half-life of an isotope, the count rate was measured at 10-min intervals for 40 min. The results are shown in Table 20.7.

Table 20.7

Time/min	0	10	20	30	40
Count rate / Counts / min	423	305	219	165	124

The background count rate was 20 counts/min.

(a) Determine the corrected count rates.

(b) Estimate the half-life of the isotope.

Solution

Subtract 20 from each count rate to obtain the corrected count rate.

Table 20.8

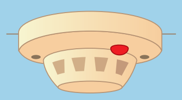
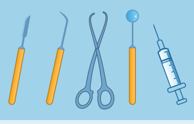
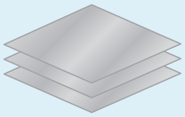
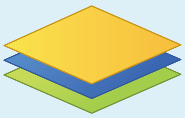
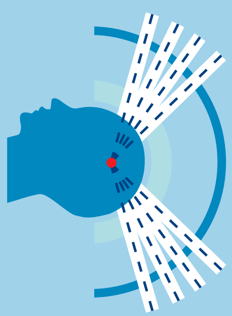
Time/min	0	10	20	30	40
Count rate / Counts / min	403	285	199	145	104

The starting count rate was about 400 counts/min. Half of this quantity is 200 counts/min. From Table 20.8, the count rate falls to this value after about 20 min. So, the half-life is about 20 min.

What are the uses of radioactivity?

Radioactive isotopes have many practical uses. Table 20.9 shows how the half-life and the type of radiation emitted determine which isotope is used for a particular application.

Table 20.9 *Some applications of radioactivity*

Application	How it works	Requirements	
		Type of radiation	**Half-life**
Household fire (smoke) alarm 	When there are smoke particles, the alarm sound because an ionising current is interrupted.	α-particles have the highest ionising ability and they are easily stopped by smoke particles. Isotope must emit α-particles.	Long (more than a few years) so that a small quantity can last a long time
Irradiating food to kill bacteria 	Radiation penetrates food and kills bacteria.	γ-rays have the highest penetrating ability. Isotope must emit γ-rays.	
Sterilisation of equipment 	γ-rays pass through sealed packages of medical equipment such as dressing, syringes and needles	Isotope must emit γ-rays.	
Measuring and controlling the thickness of materials 	• Radiation passes through continuous roll of materials. • Thickness is indicated by change in count rate.	α-particles cannot be used. They are easily absorbed. Whether to use β-particles or γ-rays depends on the type of material.	Long so that a small quantity can last for some time
	Thin materials such as paper and plastic film	β-particles can pass through these materials though some will be absorbed. Count rate will depend on thickness. γ-rays pass through too easily to show changes in count rate. Isotope should emit β-particles.	
	Materials such as metal plates	β-particles will be completely absorbed. Isotope should emit γ-rays.	
In medicine — diagnosis and treatment of cancer 	For cancer diagnosis, small doses of isotopes that emit γ-rays are taken into the body. Gamma cameras are used to obtain images for diagnosis. For cancer treatment, isotopes are inserted near the cancerous growth. γ-rays damage cancer cells, controlling and even stopping their growth.	Isotope must emit γ-rays.	Short (at most a few hours) so that they will not remain in the body
	Iodine-131 is used to treat thyroid cancer. It emits α-particles that destroy thyroid cells including the cancer cells.	Iodine -131 emits α-particles.	Short, 8 days

ENRICHMENT ACTIVITY

Doctors use radioactive isotopes called tracers to identify abnormal body processes. Tracers emit α-particles, β-particles or γ- rays and can be used to follow the path of a single element around the body.

In small groups, discuss and make a list of the advantages and disadvantages of using tracers in medicine. Present your list to the class.

Let's Practise 20.4

1 The *half-life* of a particular radioactive isotope is 15 h. A counter recorded a count rate of 8800 counts/min. It continues to record the count rate for the next 45 h.
   (a) What is half-life?
   (b) After how long will the count rate be about 4400 counts/min?
   (c) What will be the approximate count rate at the end of 45 h?

2 S On a particular day, the background count was 25 counts/min. A student measured the radiation from a radioactive isotope for 20 min. The counter showed the total number of counts as 2800. What was the count rate for the radiation from the isotope?

3 S You need to choose a radioactive isotope for a particular application. Explain the **two** properties you need to consider when making your choice.

4 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB
Exercise 20D pp. XX–XX

20.5 Safety Precautions

In this section, you will learn the following:

- State the effects of ionising nuclear radiations on living things.
- Describe how radioactive materials are moved, used and stored in a safe way.
- S Explain safety precautions for all ionising radiation.

How does ionising nuclear radiation affect living things?

Ionising nuclear radiation damages living cells. The energy carried by the radiation *can kill cells and cause mutation and cancer* (Figure 20.12).

During World War II, two Japanese cities, Hiroshima and Nagasaki, were exposed to a large amount of ionising nuclear radiation released by atomic bombs. Mutations in the genes of many survivors led to children with disabilities and health problems. The Chernobyl nuclear reactor accident in 1986 caused a large leakage of radioactive dust into the air, which led to health problems in people, livestock and plants.

In more recent times, another nuclear plant disaster had occurred. The Fukushima nuclear plant was destroyed by a tsunami in 2011. The Japanese were once again exposed to nuclear radiation. People had to abandon places contaminated by the radiation (Figure 20.13).

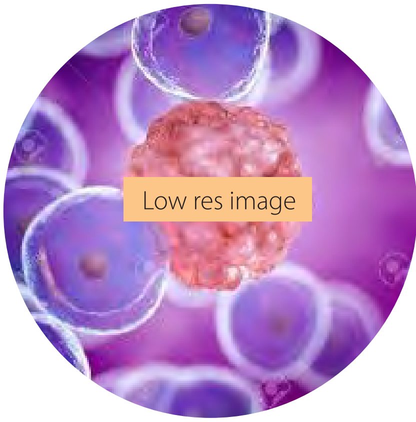


Figure 20.12 *Radiation can cause a healthy cell to become cancerous.*

Figure 20.13 *Radiation hotspot in Kashiwa, Japan*

How do we handle radioactive materials safely?

When using radioactive materials, use gloves and tongs. Wear protective clothing such as lab coats, shoe covers and safety glasses to prevent contamination. When moving a radioactive source, make sure it is in a suitable container to prevent exposure to nuclear radiation. For example, a sample of isotope that emits γ-rays must be stored in a lead box.

All radioactive materials should be kept in sealed and clearly labelled lead boxes. This is to prevent nuclear emissions from escaping into the air. The boxes should be kept in a secure place that is not easily accessible by anyone.

WORD ALERT

Accessible: easily within reach

S What safety precautions can be taken to prevent overexposure to ionising radiation?

Below are three important ways to control exposure to ionising radiation:

- *Reduce exposure time*: For example, complete the experimental setup first before introducing the radioactive source. Carry out experiments involving radioactive materials only in designated locations. These locations should only be used for work that requires the use of ionising radiation.
- *Increase distance between source and living tissue*: The intensity of all ionising radiation decreases with distance. Use long tongs or remote-controlled devices to increase the distance between radioactive materials and your body.
- *Shielding*: Use materials that absorb ionising radiation to protect your body. For example, use lead-lined gloves and suits, and thick concrete walls and lead-lined doors for rooms in which ionising radiation is used.

Let's Practise 20.5

1. State **two** negative effects of ionising nuclear radiations on living things.
2. What kind of box is suitable to store radioactive sources in a safe way?
3. S State **three** ways to control exposure to ionising radiation.
4. **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

TWB LINK

Exercises 20E–20F, pp. XX–XX

Exercise 20G Let's Reflect, p. X

Let's Map It

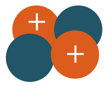
RADIOACTIVITY

Background radiation from sources including
- radon gas in the air
- rocks and buildings
- food and drink
- cosmic rays

causes

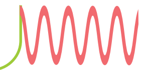
Safety precautions
- Reduce exposure time
- Increase distance from source
- Shield from source

Three types of nuclear emission



$^{4}_{2}\alpha$

$\ominus$ $^{0}_{-1}\beta$



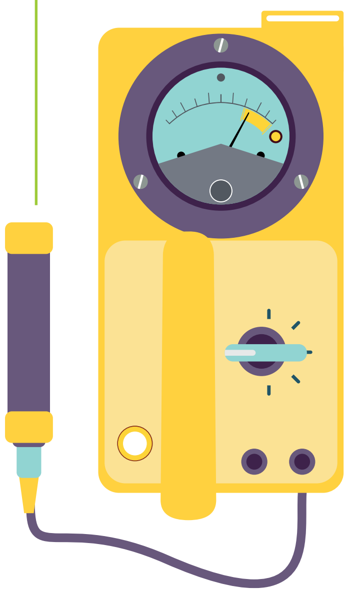
- **Alpha (α-) particle:** two protons and two neutrons
- **Beta (β-) particle:** fast-moving electron
- **Gamma (γ-) ray:** electromagnetic radiation

- Spontaneous and random emission
- Relative penetrative power
- S Relative ionisation power
- S Deflection in electric and magnetic fields

can be measured using

Electronic detector connected to a counter

- Measures count rate in **counts/s** or **counts/min**
- S **Corrected count rate** = count rate - background count rate



Radioactive decay from unstable nucleus

S Decay equations
- **α-decay**

  $^{A}_{Z}X \longrightarrow ^{A-4}_{Z-2}Y + ^{4}_{2}\alpha$
- **β-decay**

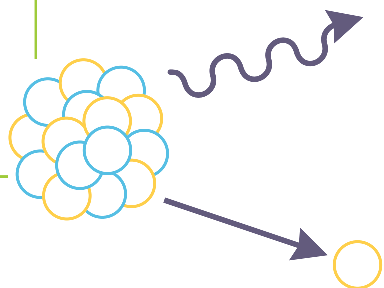
  $^{A}_{Z}X \longrightarrow {}_{Z+1}^{A}Y + ^{0}_{-1}\beta$
- **γ-emission**

  $^{Am}_{Z}X \longrightarrow ^{A}_{Z}X + \gamma$

  Or

  $^{A}_{Z}X^{*} \longrightarrow ^{A}_{Z}X + \gamma$

Half-life
- Time taken for half the nuclei of that isotope in any sample to decay.



Let's Review

Section A: Multiple-choice Questions

1 Background radiation is
A electromagnetic radiation from the Sun.
B microwave radiation from mobile phones and wireless Internet.
C ionising nuclear radiation from radioactive sources left in the laboratory.
D ionising nuclear radiation in the laboratory when there is no radioactive source present.

2 Which atoms in a sample of radioactive isotope will decay first?
A Half the atoms inside the sample
B Atoms that have lost their electrons
C Atoms near the surface because they are exposed to air
D No particular atoms because the process is random

3 Which statement about α-particles is correct?
A They emit gamma rays.
B They travel as electromagnetic waves.
C They are **not** ionising nuclear radiation.
D They are the least penetrating of the nuclear emission.

4 S Which statement about γ-emission is correct?
A They are emitted by β-particles.
B They travel at the same speed as visible light in air.
C They travel at the same speed as β-particles emitted by the same nuclei.
D The atomic number of the nucleus increases by one when it emits γ-radiation.

5 A radioactive isotope decays by emitting β-particles. What happens to an atom of the isotope when it decays?
A It gains electrons.
B It loses electrons.
C It becomes a β-particle.
D It changes into another element.

6 S The equation represents radioactive decay:
$^{227}_{89}\mathrm{Ac} \rightarrow {}^{227}_{90}\mathrm{Th} + Y$
What does *Y* represent?
A neutron
B α-particle
C β-particle
D γ-emission

7 There is 80 mg of radioactive chemical in a container. The half-life of the radioactive chemical is 5 years. The chemical decays into a stable compound. How much of the chemical is still radioactive at the end of 10 years?
A 8 mg
B 16 mg
C 20 mg
D 40 mg

8 S A student was investigating the activity of a radioactive source. When the radiation detector was placed next to the source, the count rate was 750 counts/min. The half-life of the source was 10 min. The background count rate was 30 counts/min. What was the count rate after 20 min?
A 180 counts/min
B 195 counts/min
C 210 counts/min
D 225 counts/min

9 S The isotope technetium-99m emits only γ-rays. Its half-life is six hours. It is used for detecting cancer because it
A has a short half-life.
B is a cheap source of γ-rays.
C will emit radiation for only six hours.
D takes about six hours to detect cancer cells.

10 A radioactive chemical decays by emitting β-particles and γ-rays. What type of material should be used for the container?
A lead
B plastic
C cardboard
D aluminium

Let's Review

Section B: Short-answer and Structured Questions

1 In a school laboratory, a student turns on a radiation detector for 20 min. The counter reads 440 counts. There is no radioactive material in the laboratory.

(a) What is the count rate for the radiation?

(b) What are **two** possible sources for the radiation that the detector measures?

(c) What is the name for the radiation?

2 A particular radioactive isotope decays by emitting α-particles. It has a half-life of 430 years.

(a) What is an α-particle?

(b) What does *half-life of 430 years* mean?

(c) Another radioactive isotope decays by emitting β-particles. State **two** ways in which β-particles are different from α-particles.

3 S A radioactive source is placed in a strong electric field. Figure 20.14 shows the path of the emission from the radioactive source.

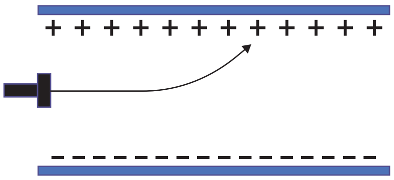


Figure 20.14

(a) Identify the type of emission. Explain your answer.

(b) Complete Figure 20.15 to show the effect on the radiation when the source is placed in a strong magnetic field. The magnetic field is at a right angle to the paper and is going into the paper.

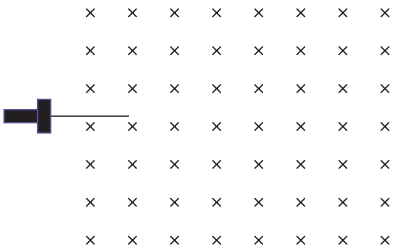


Figure 20.15

(c) Explain why long tongs should be used to pick up the source.

4 S Radioactive cobalt-60, $^{60}_{27}Co$, decays by β-emission to the element nickel (Ni) and emits γ-radiation.

(a) Write down the equation representing this decay.

(b) The half-life of cobalt-60 is 5.3 years. A container contains 16 mg of radioactive cobalt-60. After how many years will the amount of radioactive cobalt-60 be reduced to 1 mg?

5 S The isotope americium-241, $^{241}_{95}Am$, has a half-life of 430 years. It decays to form $^{237}_{93}Np$. It is commonly used in smoke detectors that makes use of ionisation. The alarm sounds when smoke breaks the flow of ions.

(a) What type of radiation does americium-241 emit that makes it suitable for use in smoke detectors? Explain the property that makes it suitable.

(b) Suggest another reason (other than the type of radiation) that makes this isotope a good choice for use in smoke detectors.

(c) In such a smoke detector, a very small quantity of americium-241 is encased in a layer of foil and ceramic. Explain why this will prevent the radiation from harming the user.

CHAPTER 21

Earth and the Solar System

PHYSICS WATCH

Scan this page to watch a clip of how the photo of Earthrise was captured.

QUESTIONS

- Why do you see only half of the Earth?
- Where on the Earth is it daytime and where is it night?
- In which direction is the Sun?
- Why do you think this photograph had a profound effect on people's feelings about the Earth? How does it affect you?

In 1968, Apollo 8 left the Earth and went into orbit round the Moon before returning to Earth. It was the first spacecraft to do so while carrying astronauts. The three crew members were looking for a future landing site on the Moon. They were photographing the brown-grey moon rocks when they noticed the Earth coming into view at another window of the spacecraft. Bill Anders, one of the astronauts, took a colour photo which is now known as 'Earthrise'. The photo had a profound effect on people's feelings about the Earth at that time.

21.1 The Earth

In this section, you will learn the following:

- Know that the Earth is a planet that rotates on its tilted axis once in about 24 hours. Use this to explain observations of the apparent daily motion of the Sun and the periodic cycle of day and night.
- Know that the Earth orbits the Sun once in about 365 days. Use this to explain the periodic nature of the seasons.
- Know that the Moon takes about one month to orbit the Earth. Use this to explain the Moon's phases.
- S Define *average orbital speed* and use the equation $v = \frac{2\pi r}{T}$.

ENRICHMENT INFO

Leap Years

Our calendars have 365 days in a year. The Earth takes closer to 365 days and six hours to travel once around the Sun. In four years, the difference between the orbit time and calendar time adds up to 24 hours. So, in every four years, an extra day is added to the calendar making a leap year. In a leap year, February has 29 days instead of 28 days.

WORD ALERT

Apparent: can be observed

How does the Earth move?

The Earth is a **planet**. Planets orbit a star. Our star is the Sun.

The Earth takes about 365 days or one **year** to orbit the Sun. Every time you celebrate your birthday, you have travelled one more time around the Sun! How many times have you travelled around the Sun?

The Earth also rotates on its axis and it takes about 24 hours or one **day** *to rotate once*. The Earth's *axis is tilted* at an angle of about 23.5 degrees towards the plane of its orbit.

How does day and night come about?

Stars produce energy by nuclear fusion and give out light so they shine brightly. A planet only shines when the light from a star lands on it.

The Sun shines on the half of the Earth that is facing it. This half experiences daytime. The other half is in darkness, which experiences night-time. In 24 hours, the Earth spins once and we move from the light into darkness and back into the light again.

On the Earth, we see the Sun move across the sky from East to West. This apparent movement is because the Earth is spinning about its axis as it orbits the Sun.

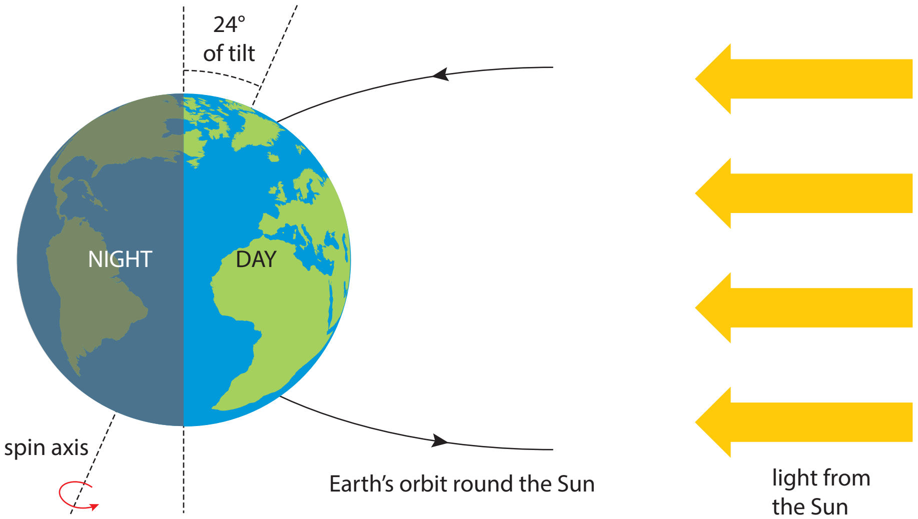


Figure 21.1 *The day and night cycle is due to the Earth's rotation about its tilted axis.*

What is a season?

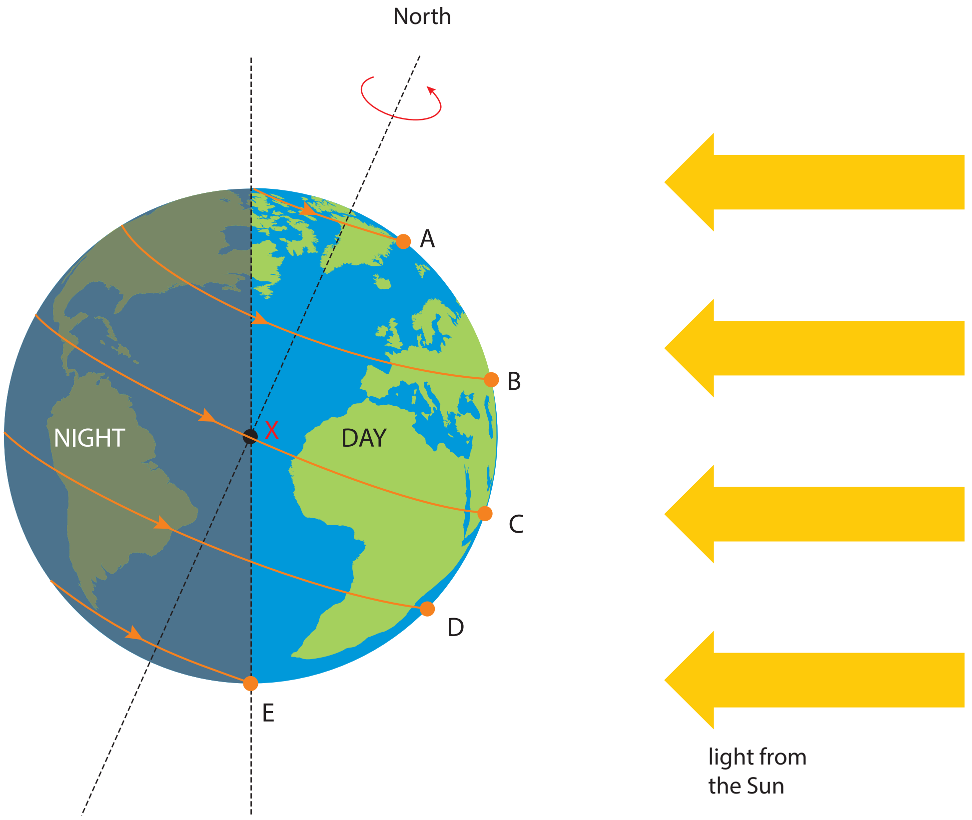
Temperate countries have different weather patterns at different times of the year. These weather patterns are called **seasons**. There are four seasons every year — spring, summer, autumn and winter.

Seasons occur because the Earth orbits the Sun on a tilt. At different times of the year, places on the Earth receive different amounts of the Sun's rays.

Figure 21.2 shows how the tilt of the Earth's axis affects the periods of daytime and night-time. Here, the North Pole is tilted directly towards the Sun.

WORD ALERT

Temperate: having moderate climate, experienced by countries between the tropics and the polar regions of the Earth



QUICK CHECK

Refer to Figure 21.2.

Point X is experiencing dawn. Night has just ended and daytime is starting.

True or false?

A is at the Arctic Circle. Places north of this circle will be in daylight for 24 hours and the Sun never sets.

B is in the temperate zone between **A** and **C**. Places here have longer days and shorter nights.

C is on the Equator. Places around the Equator have equal periods of daytime and night-time.

D is in the temperate zone between **C** and **E**. Places here have shorter days and longer nights.

E is at the Antarctic Circle. Places south of this circle will be in darkness for 24 hours and the Sun never rises.

Figure 21.2 *The tilt of the Earth's axis causes different parts of the Earth to have different lengths of daytime and night-time.*

Figure 21.3 shows the Earth in its orbit at different times of the year and the corresponding seasons for the Northern Hemisphere.

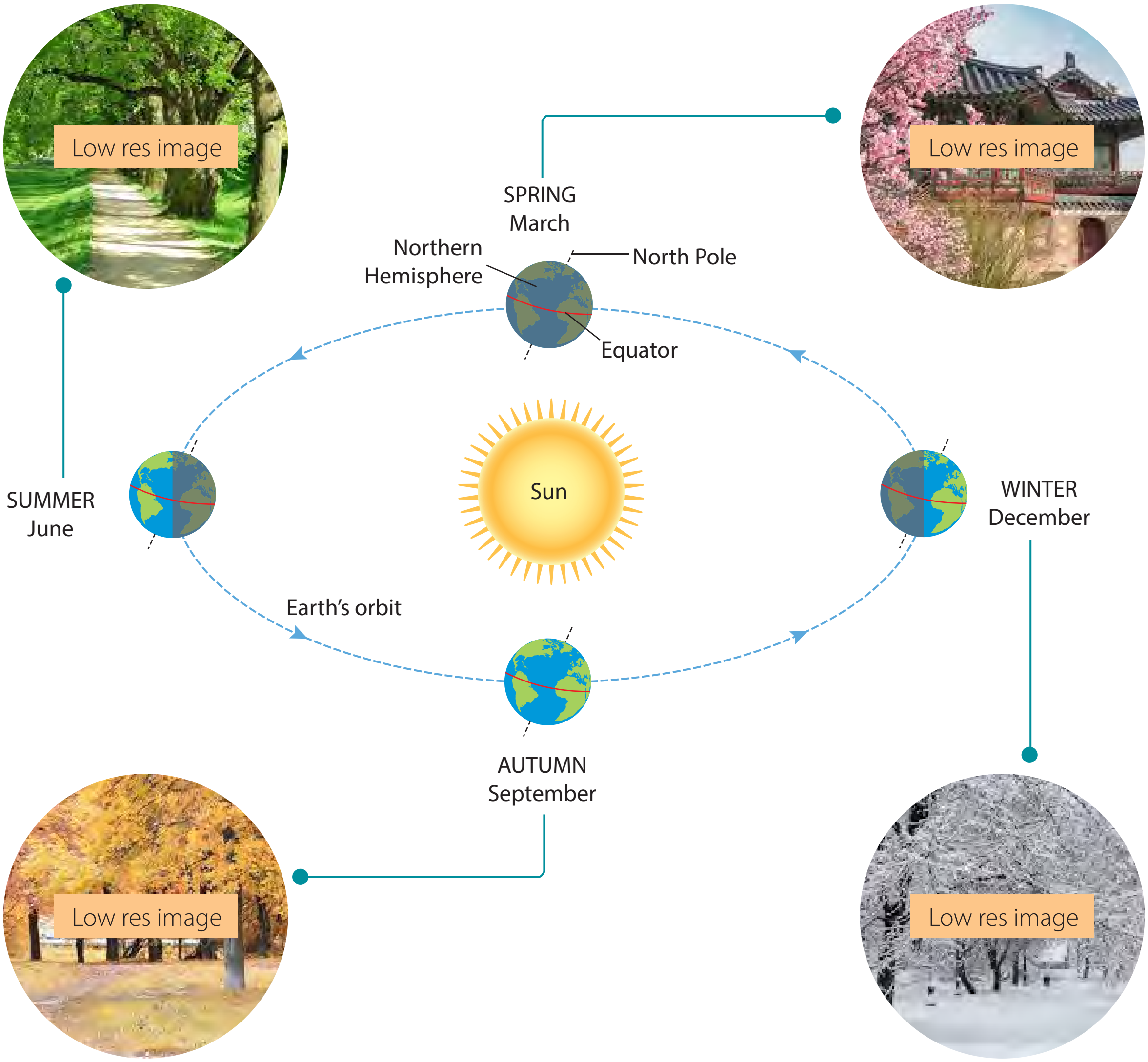


Figure 21.3 *The seasons in the Northern Hemisphere (not to scale).*

In the months around June, the tilt of the North Pole is towards the Sun. As shown in Figure 21.3, the Northern Hemisphere, above the Equator, will have long days and short nights. It is hotter because the Sun rises higher in the sky and there are more hours of sunshine. This is the summer season.

As the orbit continues, the Earth's axis no longer tilts towards the Sun. In September, the Northern Hemisphere is tilted in the direction of travel. The days gradually become shorter and the nights longer. Shorter days mean cooler temperatures, and it is autumn.

Around December, the tilt of the North Pole will be away from the Sun. In the Northern Hemisphere, the days will be shortest and the nights longest. Fewer hours of sunlight and the Sun rises lower in the sky means it will be colder. This is winter.

In March, the Northern Hemisphere is tilted in the direction of travel again. The days gradually become longer and the nights shorter. The land will be warming up again as spring arrives.

ENRICHMENT *ACTIVITY*

Figure 21.3 is certainly not drawn to scale. Try this to see why!

Earth's radius = 6×10^6 m
Sun's radius = 7×10^8 m

Radius of Earth's orbit = 1.5×10^{11} m

If the Sun's radius was reduced to 5mm, what would the distance between the Sun and the Earth be to the same scale? On this same scale, what would the Earth's radius be?

QUICK CHECK

Look at the Southern Hemisphere in Figure 21.3. It will be winter in June and summer in December.

True or false?

How does the Sun appear to move during the day?

Remember that the Sun appears to move across the sky because the Earth is spinning about its axis as it orbits the Sun. The Earth spins from West to East, so the Sun appears to rise in the East and set in the West.

At the Equator, the Sun always rises due east and sets due west, so the days and nights are always 12 hours long. The Sun is almost directly overhead at midday all year. Places near the Equator have little seasonal change because the Sun's position in the sky does not change very much all year.

In the Northern Hemisphere, the Sun's path across the sky is longer in summer than in winter. Also, the Sun rises higher in the sky in summer than in winter.

Light from the Sun is more intense when it is higher in the sky as the rays spread over a smaller area of the Earth.

Figure 21.4 shows the apparent motion of the Sun in the sky for Manchester in the UK. Manchester is about 53 degrees north of the Equator. On the longest day of the year, June 21st, there is 17 hours between sunrise and sunset. On the shortest day, December 21st, there is only 7.5 hours of daylight.

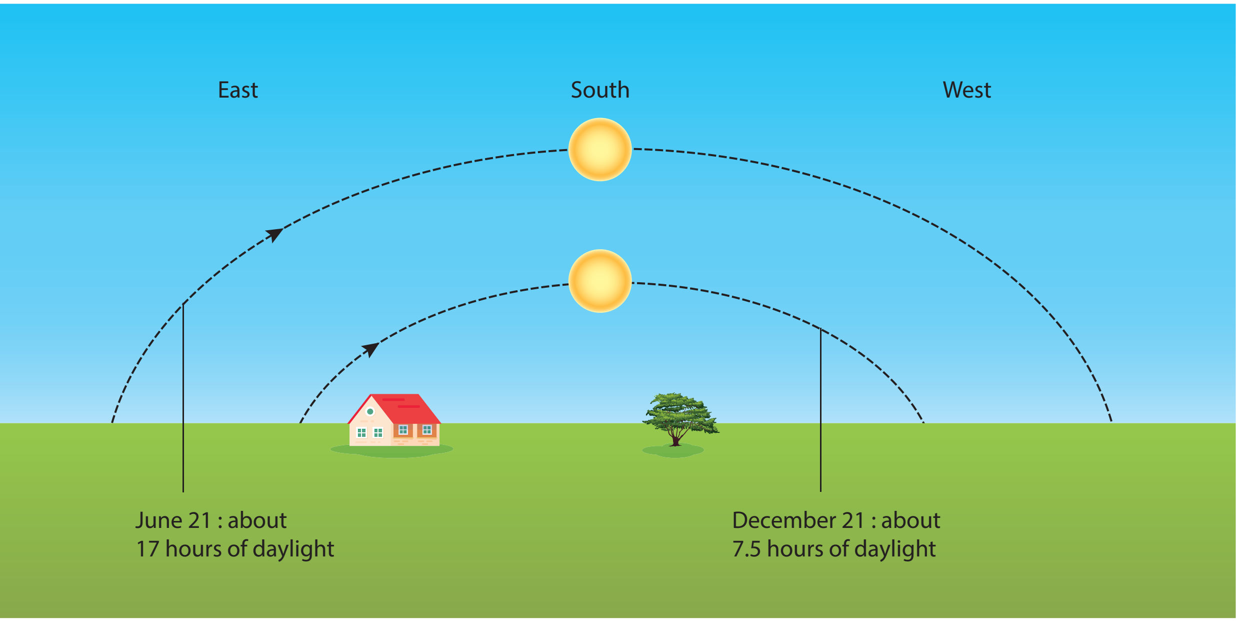


Figure 21.4 *The Sun's apparent movement across the sky 53 degrees north of the Equator.*

Why does the Moon's appearance change?

Some planets have *natural satellites* or *moons* that orbit them as they orbit the Sun. The Earth has one natural satellite called the **Moon**. Like the planets, moons do not give out light. We only see the Moon's surface when light is reflected back from it.

The Moon takes approximately 28 days to orbit the Earth once. It orbits the Earth with the same side facing the Earth as it travels round.

HELPFUL NOTES

You must **never** look directly at the Sun. A glass lens can focus the Sun's rays to set fire to paper. Your eye lens would focus the Sun's energy onto the light sensitive cells of your eye and damage them.

PHYSICS WATCH

Scan this page to watch how the Sun appears to move across the sky. They are taken at the same place on the longest day and the shortest day.

What differences do you expect to see?

QUICK CHECK

The Sun moves across the sky in the daytime because it is orbiting around the Earth.

True or False?

ENRICHMENT ***ACTIVITY***

Make a record of the Moon's appearance. Observe the Moon every day for 28 days. Note the date and the time you made the observation. Draw a circle to represent the Moon and shade in the dark part to record its appearance. Use Figure 21.5 on page 352 to show where the Moon is in its orbit round the Earth.

ENRICHMENT *INFO*

The Sun is about 400 times further from the Earth than the Moon. The Sun's diameter is about 400 times greater than the Moon's. So, the Sun and Moon appear to be the same size in the sky.

Occasionally, for some places on Earth, a new Moon coincides exactly with the Sun. The Moon completely blocks out the Sun. This is called a *total eclipse*. The Sun disappears and daytime turns to night-time for a few minutes.

The appearance of the Moon in the sky changes from day to day. This depends on the Moon's position relative to the Sun and the Earth. The different appearances are known as the **phases of the Moon**.

Study Figure 21.5. The Earth, with the Moon at different positions in its orbit (inner circle), is shown as viewed *from above the North Pole*. The Moon is also shown as how it appears *from the Earth* at those different positions (outer circle).

One half of the Moon is in sunlight, so the Moon is always half-illuminated. When the Moon is in position 1, the bright half of the Moon is facing the Earth. On the Earth, you would see a bright round **full Moon** in the sky at night.

As the Moon continues its orbit, less and less of the bright half of the Moon is facing the Earth, and more and more of the dark side of the Moon is seen. Positions 2, 3 and 4 in Figure 21.5 shows how the Moon appears from Earth as the bright part is getting smaller or **waning**.

In position 5, the dark side of the Moon is facing the Earth. This is called the **new Moon**. It is only illuminated by a little light reflected from the Earth. This occurs in daytime so the new Moon is not visible.

In the rest of its orbit, more and more of the bright part of the Moon can be seen from the Earth. The Moon is said to be **waxing**.

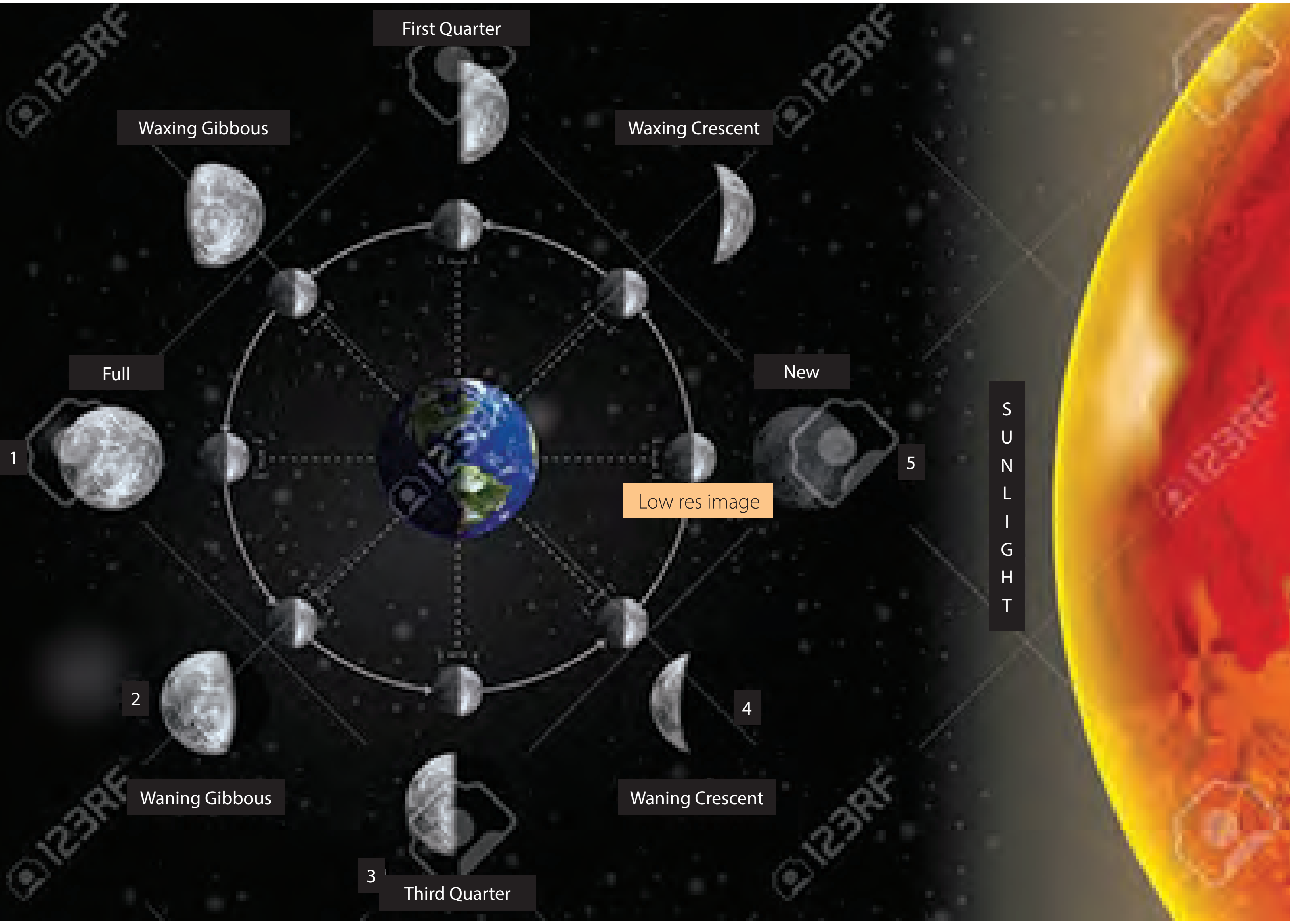


Figure 21.5 *The phases of the Moon (not to scale).*

How quickly is the Moon orbiting the Earth?

Remember that speed is distance travelled per unit time and average speed is given by the equation:

$v = \frac{s}{t}$ where v = average speed (in m/s)

s = total distance travelled (in m)

t = total time taken (in s)

For a circular orbit, the total distance for one orbit would be the circumference of a circle.

Circumference = $2\pi r$ where r = average orbital radius

The Moon's orbit around the Earth is a slightly squashed circle called an *ellipse*.

But if we use the average radius of the orbit, we can use the following equation for the **average orbital speed**:

$\boldsymbol{v = \frac{2\pi r}{T}}$ where v = average orbital speed (in m/s)

r = average orbital radius

T = orbital period

Worked Example 21A

It takes 27.3 days for the Moon to travel once around the Earth. The average radius of the Moon's orbit is 385 000 km. Calculate the average orbital speed of the Moon.

Solution

First, we must convert the units.

Average radius = 385 000 km = 3.85×10^8 m

Orbital period = $27.3 \times 24 \times 60 \times 60 = 2.36 \times 10^6$ s

Average orbital speed = $\frac{2\pi r}{T} = \frac{2(3.85 \times 10^8)}{2.36 \times 10^6} = 1.03 \times 10^3$ m/s

LINK

Recall what you have learnt in Chapter 2 about speed and average speed.

Let's Practise 21.1

1 Choose from the words below to complete the sentences.

natural satellite *planet* *star*

The Earth is a ________ which orbits a ________ called the Sun.
The Moon is a ________ of the Earth.

2 State how many times the Earth spins on its axis every year.

3 Which is the correct reason for the Sun's apparent movement across the sky every day?

A The Sun's rotation about its axis.

B The Earth's rotation about its axis.

C The Sun's rotation around the Earth.

D The Earth's rotation around the Sun.

4 State whether each of these statements is true or false.

(a) A new Moon occurs when the dark side of the Moon faces the Earth.

(b) A full Moon occurs when the dark side of the Moon faces the Earth.

(c) A first quarter Moon occurs when half of the bright side is seen and this part is decreasing.

(d) A waxing crescent Moon occurs when a sliver of the bright side is seen and this part is increasing.

WORD ALERT

Sliver: small, thin and narrow part of something

LINK TWB

Exercise 21A, pp. XX–XX

5 S The International Space Station orbits the Earth 410 km above its surface. It takes 92 minutes to complete one orbit. Work out its average orbital speed in m/s. (Take the radius of the Earth to be 6 400 km.)

6 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

21.2 The Solar System

In this section, you will learn the following:

- Describe the Solar System.
- Know the physical difference between the four planets nearest to the Sun and the four planets furthest from the Sun. Explain this difference.
- Know what affects the strength of a planet's gravitational field.
- Know that planets orbit the Sun due to the mass of the Sun.
- Know that the Sun's gravitational attraction keeps an object in orbit around the Sun.
- Calculate the time it takes for light to travel between objects in the Solar System.
- S Know that planets, minor planets and comets have elliptical orbits and that the Sun is not at the centre except when the orbit is nearly circular.
- S Know that an object in an elliptical orbit travels faster when closer to the Sun and explain this using the conservation of energy.
- S Analyse and interpret planetary data.
- S Know how the Sun's gravitational field decreases with distance and how this affects the orbital speed of the planets.

How was the Solar System formed?

The Earth, Sun and Moon are part of our Solar System. Figure 21.6 shows the main known objects lined up. The diagram is certainly not to scale — most of the Solar System is empty space.

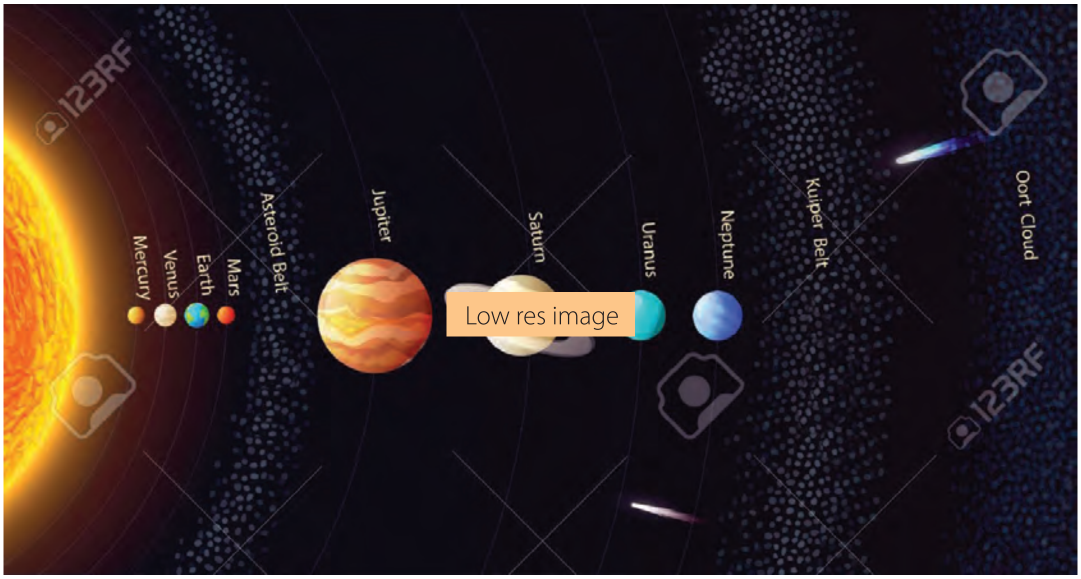
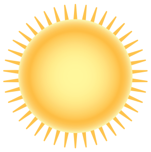


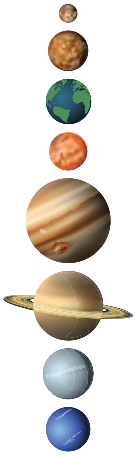
Figure 21.6 Diagram showing the main objects in our Solar System

Table 21.1 gives more information about the main objects in our Solar System.

Table 21.1 *Main objects in our Solar System*



One star called the **Sun** is at the centre of our Solar System.

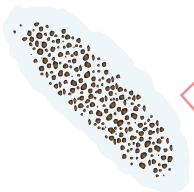


Eight **planets** orbit the Sun.

- In order of their distance from the Sun, these are called Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus and Neptune.
- Mercury, Venus, Earth and Mars are smaller rocky planets. Jupiter, Saturn, Uranus and Neptune are larger planets made from gas and ice.

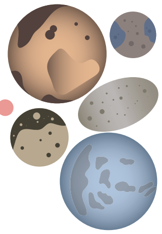
Most of the eight planets have one or several moons. A **moon** is a natural satellite which orbits a planet. The Earth has just one moon. Saturn has over 50 moons.

The **asteroid belt** between Mars and Jupiter contains many asteroids. Ceres is the only object in the asteroid belt which is large enough to be classified as a dwarf planet.

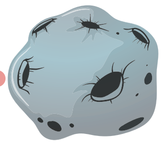


The **Oort cloud** is thought to contain icy rocks and dwarf planets like the Kuiper belt. It is also home to comets with orbit times longer than 200 years.

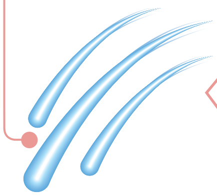
Other objects in the Solar System that orbit the Sun are **minor planets** which include:



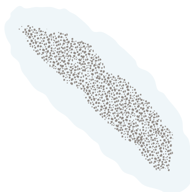
Dwarf planets — these are less massive than the eight planets but are also almost spherical. Their gravity is not enough to attract nearby matter, so there may be other objects in their orbit. Pluto is a dwarf planet in the Kuiper belt with a very elliptical orbit.



Asteroids — these are irregularly shaped lumps of rock left over from the formation of the Solar System. Asteroids have elliptical orbits.



Comets — these are lumps of frozen gases and dust left over from the birth of the Solar System and they have very elliptical orbits.



The **Kuiper belt** beyond Neptune contains more leftovers from Solar System. It has asteroids and other dwarf planets as well as Pluto. Comets with orbit times of less than 200 years, such as Halley's comet, originate here.

About 4.6 billion years ago, the Solar System was formed from a swirling cloud of gas and dust in space. These clouds called **nebulae** consist of mainly hydrogen plus a mixture of heavier elements. The particles in the cloud were attracted to each other because of the force of gravity between them.

Gradually, the cloud began to collapse which made it spin faster. Gravitational potential energy became kinetic energy as the particles began to move. Then kinetic energy became heat energy as they crashed together. A hot spinning mass called a **protostar** was formed at the centre of a swirling disc of gas and dust. The swirling disc is called an **accretion disc**.

Accretion is the accumulation of particles into a massive object by gravitational attraction.

Eventually, the protostar became dense and hot enough for nuclear fusion to occur at its centre. It became a star — the Sun — and began to give out an enormous amount of energy.

ENRICHMENT *INFO*

Pluto

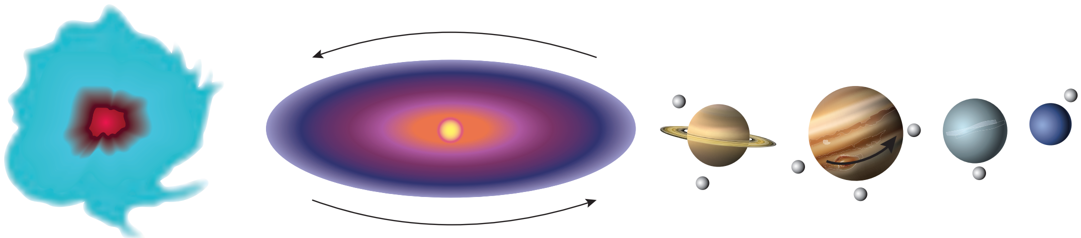
Pluto was discovered in 1930 and declared to be the ninth planet of the Solar System. After 1992, it was found to be less massive than previously thought, so it was reclassified as a dwarf planet.

LINK

Recall what you have learnt in Chapter 3 about gravity.

Recall what you have learnt in Chapter 6 about gravitational potential energy and kinetic energy.

The matter in the spinning disc also gradually clumped together to become the rest of the Solar System. The four rocky planets formed from heavier material that was pulled near the Sun by its force of gravity. Lighter gases collected further away, forming the four gas giants.



▲ A cloud of dust and gas, a **nebula**, is pulled inwards by the force of gravity.

▲ A protostar is formed at the centre with a disc of gas and dust swirling round it.

▲ The central mass becomes a star. Matter in the disc collects to form the planets, moons and asteroids.

Figure 21.7 *The stages in the birth of the Solar System.*

WORD ALERT

Nebula: singular of nebulae

What determines gravitational field strength?

Particles of gas and dust are small and have little mass. So their gravitational field strength is small and the force of attraction is weak. As they clump together, the mass and the gravitational field strength will increase. It will attract other particles with more force. The process is very slow at first but gradually speeds up. It takes millions of years for a cloud of dust and gas to form a Solar System.

The Sun contains 99% of the matter in the Solar System, so its gravitational field is very strong. This is why it pulls the planets into orbit around it and they do not fly off into space. The gravitational field strengths of the planets are much weaker in comparison because they have much less mass.

Gravitational fields around the Sun and the planets extend into space. The further away the distance from the Sun or the planets, the weaker the gravitational field becomes.

LINK

The speed of light is 3×10^8 m/s. At what speed do radio waves travel in space?

Recall what you have learnt in Chapter 13 about electromagnetic waves.

How big is the Solar System?

In 1977, the US space agency NASA launched two unmanned space craft from the Earth. In 1989, one of these, called Voyager 2, arrived close to Neptune, the furthest planet from the Sun (Figure 21.8). It sent pictures of Neptune back to Earth using radio signals. Radio signals are carried by radio waves that are electromagnetic waves and travel at the fastest speed possible. How long do you think it took the signals to get back to Earth? See Worked Example 21B.

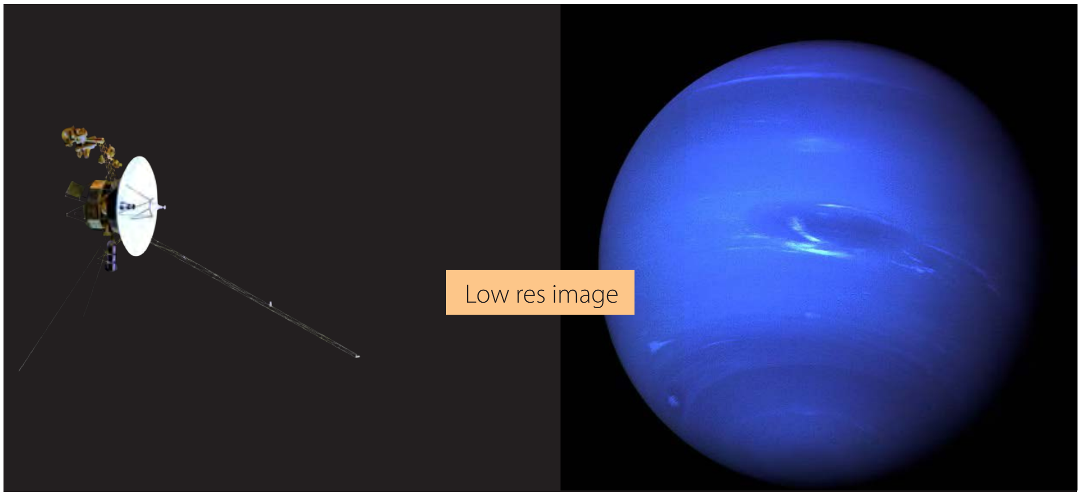


Figure 21.8 *Voyager 2's encounter with Neptune*

Worked Example 21B

When Voyager 2 was close to Neptune, it was about 4.5×10^9 km from the Earth. It sent radio signals back to Earth. Calculate how long it took the signals to reach the Earth.

Solution

First, we must rearrange the equation for speed: $v = \frac{s}{t}$

$t = \frac{s}{v}$

Distance $= 4.5 \times 10^9$ km $= 4.5 \times 10^{12}$ m

Speed $= 3 \times 10^8$ m/s

$\therefore$ Time $t = \dfrac{4.5 \times 10^{12}\text{ m}}{3 \times 10^8\text{ m/s}} = 15\,000\text{ s} = 4.2\text{ h}$

What are the shapes of orbits?

Long ago, astronomers thought that all orbits were perfect circles. Detailed observations and measurements showed that objects in the Solar System move in an **elliptical orbit**. Remember that the Moon's orbit round the Earth is slightly elliptical — like a squashed circle. The eight planets also have slightly elliptical orbits with the Sun near the centre. Some minor planets and moons have orbits that are more elliptical. Figure 21.9 shows how the shape of an ellipse is obtained using two foci.

Comets have very elliptical orbits. The Sun is not at the centre of the ellipse but at one focus. Comets are lumps of frozen gases and dust left over from the birth of the Solar System. They come from either the Kuiper belt or the Oort cloud, and they orbit the Sun.

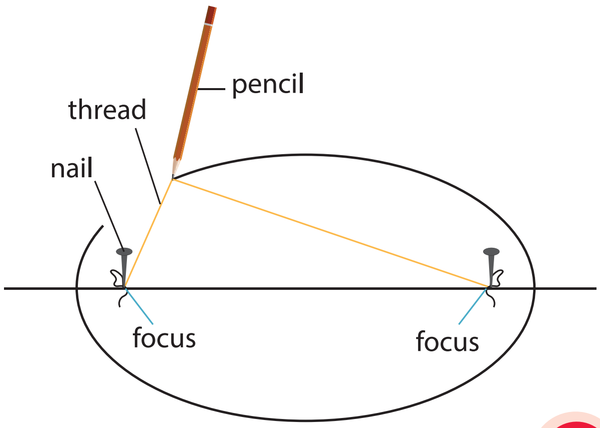


Figure 21.9 *Ellipse showing the two foci*

When a comet is furthest from the Sun, it travels very slowly (Figure 20.10). Here, its kinetic energy is the lowest. The Sun's gravitational field pulls the comet towards it, so the comet speeds up. The gravitational force is greatest nearest the Sun. Here, the comet moves the fastest and its kinetic energy is the greatest. It starts to slow down as it moves away from the Sun again.

By the principle of conservation of energy, kinetic energy changes into gravitational potential energy as the comet moves away from the Sun. Gravitational potential energy changes back to kinetic energy as it moves towards the Sun.

Also the increased heat energy near the Sun causes some of the comet's frozen gas to evaporate. This creates a long bright tail streaming away from the direction of the Sun, making the comet visible. The bright tail disappears as it moves away again.

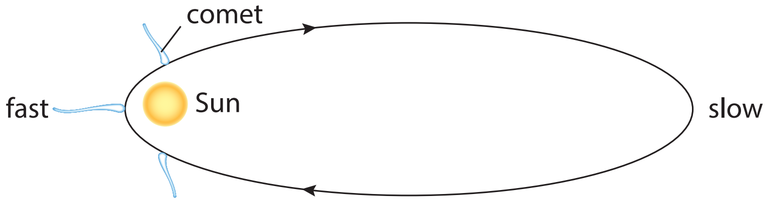


Figure 21.10 *Some stages in the path of a comet round the Sun*

WORD ALERT

Foci: centres, points, pivots

Focus: singular of foci

QUICK CHECK

A comet has the greatest gravitational potential energy when it is closest to the Sun. It has the least gravitational potential energy when it is furthest away from the Sun.

True or false?

Figure 21.11 Halley's comet

Perhaps the most famous comet is Halley's comet (Figure 21.11). It was first recorded by Chinese astronomers in 239 BC and is visible from the Earth for a short time every 79 years. Halley's comet orbits the Sun in the opposite direction to the planets.

What determines the orbital speed of the planets?

Table 21.2 shows some data from NASA about the eight planets.

Table 21.2 *Data about the eight planets of the Solar System from NASA*

	Average distance from the Sun/ millions of km	Approx. mass compared with the Earth	Approx. density/ kg/m^3	Gravitational field strength compared with the Earth	Time to spin in Earth days	Time to orbit in Earth years	Approx. range of surface temps/°C
Mercury	58	0.05	5400	0.4	180	0.2	–170 to 450
Venus	110	0.8	5200	0.9	120	0.6	465
Earth	150	1	5500	1	1	1	–89 to 58
Mars	230	0.1	3300	0.4	1	2	–125 to 20
Jupiter	780	320	1300	2.4	0.4	12	–110
Saturn	1400	95	680	0.9	0.4	30	–140
Uranus	2900	15	1300	0.9	0.7	84	–195
Neptune	4500	17	1600	1.1	0.7	164	–200

S

Look at the columns of the distance from the Sun and the time to orbit. Can you see a pattern between them?

As the distance from the Sun increases, the time to orbit the Sun also increases. Nearer to the Sun, the gravitational field is stronger. The force on the inner planets pulls them into a tighter circle. They have a greater speed and have less distance to travel, so the time to orbit is much less.

ENRICHMENT
THINK

Would humans be able to survive on any other planet apart from the Earth. If no, why? If yes, what would they need from the Earth? What other information about the planets will you need to find out?

Let's Practise 21.2

1 **(a)** List the eight planets of our Solar System in order of increasing distance from the Sun.
(b) What is the difference between the nature of the four planets nearest the Sun compared with the four furthest away?

2 State the energy conversions that take place when the material in a cloud of dust and gas clumps together.

3 Explain what is meant by the following terms:
(a) moon **(b)** asteroid **(c)** protostar

4 The Sun is 150 million kilometres from the Earth. Work out how long it takes the light from the Sun to reach the Earth. (The speed of light in a vacuum is 3×10^8 m/s.)

5 S Use Table 21.2 to answer the following questions.
(a) What is unusual about the temperature on Venus?
(b) Which planet has a gravitational field strength similar to the Earth's?
(c) Which planet is the most massive?
(d) Which planet takes the longest to spin on its axis?
(e) The asteroid belt lies between Mars and Jupiter. Estimate the time in Earth years for an asteroid in this belt to orbit the Sun.

6 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

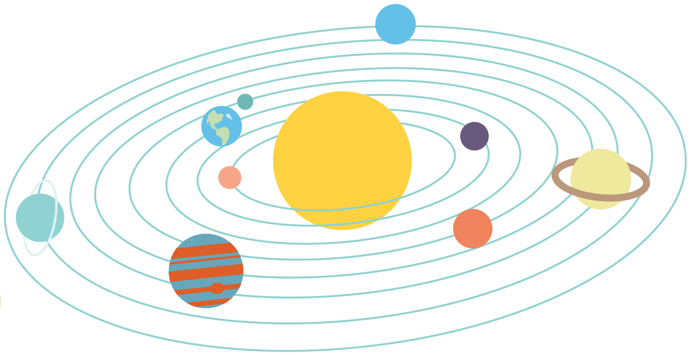
Exercises 21B–21C, pp. XX–XX

Exercise 21D Let's Reflect, p. XXX

Let's Map It

Cloud of dust and gas
- Mainly hydrogen and helium plus assorted heavier elements

the force of gravity causes matter to collect together—accretion—to form



SOLAR SYSTEM

consists of

Main planets
- Mercury
- Venus
- Earth
- Mars

rocky and small

- Jupiter
- Saturn
- Uranus
- Neptune

gaseous and large

The Sun
- A star
- Massive size produces strong gravitational field
- Gives out energy

- Dwarf planets
- Moons
- Asteroids
- Comets

S Gravitational field strength
- Increases with mass
- Decreases with distance from planet

The Earth
- Spins once every 24 hours to give **night and day**
- Orbits the Sun every year (~365 days) on its tilted axis to give **seasons**

The Moon
- Earth's natural satellite
- Orbits the Earth every 27 days
- Appearance changes with position in orbit **(Moon phases)**

Orbits
- Kept in orbit by the Sun's gravitational attraction
- S Elliptical orbit with the Sun at one focus
- S Orbital speed $v = \frac{2\pi r}{T}$
- Time to orbit increases as distance from the Sun increases

Let's Review

Section A: Multiple-choice Questions

1 Which statement is incorrect?

A The Moon is a natural satellite of the Earth.
B The Earth spins on its axis once a year.
C The Sun is the star at the centre of the Solar System.
D The Solar System was produced from a cloud of dust and gas.

2 S An astronaut goes to Mars where the gravitational field strength is 40% of that of the Earth. Which statement correctly describes his mass and weight on Mars compared with the Earth?

A Same mass and same weight
B Smaller mass and same weight
C Same mass and smaller weight
D Smaller mass and smaller weight

Section B: Short-answer and Structured Questions

1 Explain why half of the Earth has 12 hours of night-time followed by 12 hours of daytime.

2 Choose the correct word to complete the sentences below which describe the seasons.

In December, the South Pole of the Earth is tilted ______________ (*towards/away from*) the Sun. The temperate countries in the ______________ (*Northern/Southern*) Hemisphere will have long days and short nights. The ________________ (*Arctic/Antarctic*) Circle will have 24 hours of daytime. In the Northern Hemisphere, it is _________________ (*summer/winter*).

3 **(a)** Draw a diagram to show how the Sun, Earth and Moon are positioned when a full Moon is seen.

(b) Assuming that the Moon takes exactly 28 days to orbit the Earth. Describe the appearance of the Moon

(i) 7 days;
(ii) 14 days;
(iii) 21 days

after the full Moon.

4 S Figure 21.12 shows three stages in the formation of our Solar System. Explain what is happening in each stage.

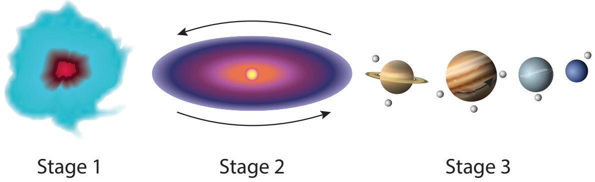


Figure 21.12

5 S Figure 21.13 shows the orbit of a comet around the Sun.

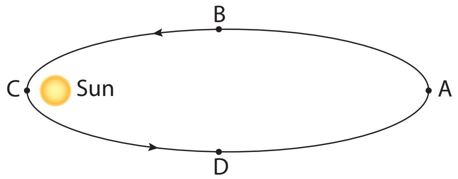


Figure 21.13

(a) Explain what a comet is.
(b) Give the name of this shape of orbit.
(c) At which point in the orbit is the comet travelling slowest?
(d) At which point in the orbit does the comet have the most kinetic energy. Explain your answer.
(e) At which point in the orbit is the comet's energy changing from kinetic energy to gravitational potential energy.
(f) Halley's comet orbits the Sun every 79 years. Give **two** reasons why it is only visible from the Earth for a few days each orbit.

6 S Geostationary satellites are used to transmit communication signals from one continent to another. They orbit above the same place on the equator.

(a) Explain why their orbit time must be 24 hours.
(b) These satellites orbit at a height of 36 000 km above the surface of the Earth. Work out their average orbital speed.
(Take the radius of the Earth to be 6 400 km.)

CHAPTER 22

Stars and the Universe

Credit: NASA, ESA, and T. Brown (STScI), W. Clarkson (University of Michigan-Dearborn), and A. Calamida and K. Sahu (STScI)

PHYSICS WATCH

Scan this page to watch a clip about the Hubble telescope and its contribution to astronomy.

Nancy Roman was interested in astronomy from an early age. Her mother used to take her out at night and teach her the constellations. When she became NASA's first chief of astronomy, she campaigned for a telescope to be launched into space in order to see the Universe more clearly. The Hubble space telescope was launched in 1990. Roman is called the 'mother of Hubble.'

The photo shows clusters of stars captured by the Hubble space telescope using its wide field camera. China, one of the Asian space powers, is planning to launch its own space telescope. It will have a much wider field of view than the Hubble telescope and will enable us to see more spectacular images of stars that we have never seen before.

QUESTIONS

- Why should the Hubble space telescope see space more clearly than a telescope on Earth?
- What differences can you observe in the appearance of the stars?
- How does this image compare with the stars that you can see at night from where you live?

22.1 The Sun as a Star

In this section, you will learn the following:

- Know that the Sun is a medium-sized star, consisting mostly of hydrogen and helium.
- Know that the Sun radiates most of its energy in the infrared, visible and ultraviolet regions of the electromagnetic spectrum.
- **S** Know that stars are powered by nuclear reactions that release energy.
- **S** Know that in stable stars the nuclear reactions involve the fusion of hydrogen into helium.

HELPFUL NOTES

The volume of the Sun is big enough for over a million Earths to fit inside!

How big is the Sun?

The Sun is a massive ball of mainly hydrogen and helium gases. It is the biggest object in the Solar System. The next biggest object is Jupiter — ten Jupiters would fit across the width of the Sun.

The Sun is massive enough for nuclear reactions to take place at its centre. These nuclear reactions produce enormous amounts of energy. The Sun radiates the energy in the form of electromagnetic radiation — mostly infrared, visible light and ultraviolet. Without this energy, life would not be possible on the Earth.

The Sun is one of many, many stars in the Universe. Compared with these stars, the Sun is an average yellow star. Some stars are bigger, hotter and bluer than the Sun, and some are smaller, cooler and redder.

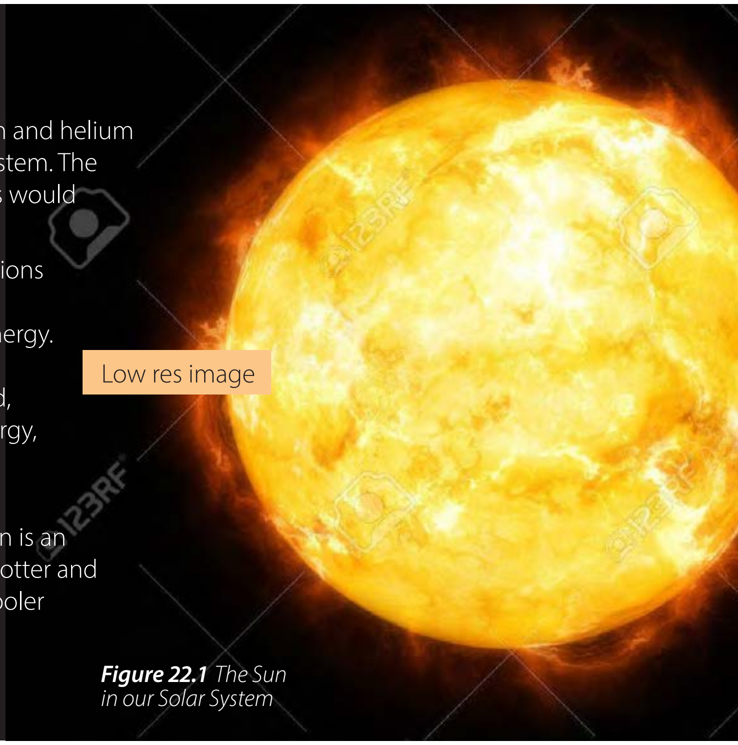


Figure 22.1 *The Sun in our Solar System*

LINK

Recall what you have learnt in Chapter 13 about electromagnetic radiation.

QUICK CHECK

The Sun is the biggest object in the Universe.

True or False?

S How do stars produce energy?

Stars are so massive that the density and temperature at the centre are high enough for nuclear reactions to occur. Positively charged hydrogen nuclei are able to overcome their electrostatic repulsion and combine or fuse together to become helium nuclei. When this nuclear fusion happens, a lot of energy is released. In this part of its life, the star is stable.

The Sun is a stable star. It has been shining for about 5000 million years. Although it consumes about 600 million tonnes of hydrogen each second, there is enough for nuclear fusion to continue for another 5000 million years.

Let's Practise 22.1

1 State whether each statement is true or false.
   - **(a)** The Sun is made of gases.
   - **(b)** The Sun is nearly at the end of its life.
   - **(c)** **S** Nuclear fission occurs in the centre of the Sun.
   - **(d)** **S** Smaller nuclei combine to make larger ones in the core of the Sun.

2 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK TWB

Exercise 22A, pp. XX–XX

22.2 Stars

In this section, you will learn the following:

- State that galaxies are each made up of many billions of stars.
- State that the Sun is a star in the galaxy known as the Milky Way.
- State that other stars that make up the Milky Way are much further away from Earth than the Sun is from the Earth.
- State that astronomical distances can be measured in light-years.
- S Know that one light-year is equal to 9.5×10^{15} m.
- S Describe the life cycle of a star.

What is the Milky Way?

On a really clear night and far away from bright city lights, you might be able to see a faint band of light stretching across the sky (Figure 22.2). This is the **Milky Way**. It is a group of many billions of stars or a **galaxy** to which our Sun belongs.

The Milky Way is a flattish spiral galaxy with a bulge at the centre. Our Solar System is in one of the spiral arms. If we could see it from above, it would look like the artist's impression in Figure 22.3.

WORD ALERT

Billion: a thousand million or 1 000 000 000

Figure 22.2 The Milky Way seen from the Earth

Figure 22.3 Artist's impression of the Milky Way galaxy viewed from above

QUICK CHECK

The bright star Sirius is 8.6 ly away from the Earth. It has taken the light from Sirius 8.6 years to reach the Earth.

True or False?

ENRICHMENT *INFO*

You can see the value for the distance of the light-year in metres by rearranging the equation for speed: $v = \frac{s}{t}$

to give $s = vt$.

The speed of light v $= 3 \times 10^8$ m/s

The time $t = 1$ year

$= 365 \times 24 \times 60 \times 60$ s

$= 3.15 \times 10^7$ s

The distance s

$= 3 \times 10^8 \times 3.15 \times 10^7$

$= 9.5 \times 10^{15}$ m or

9 500 000 000 000 000 m

QUICK CHECK

It will be 5000 million years before the Sun becomes a red giant.

True or False?

The closest star to the Sun in the Milky Way galaxy is called Proxima Centauri. It is about 38 million billion metres away. Distances in the Milky Way are so big that it is more convenient to use a larger unit of distance.

Light travels at the fastest speed possible and it takes light from Proxima Centauri about four years to reach the Earth. We call the distance that light travels in one year *a light-year*. So Proxima Centauri is about four light-years (4 ly) from the Earth.

1 light-year is the distance that light travels in one year in the vacuum of space. It is equal to **9.5×10^{15} m**.

How do stars die?

You have learnt in Chapter 21 that a star is formed from a nebula, which is a cloud of dust and mainly hydrogen gas in space. Gravitational attraction causes the cloud to collapse. A hot spinning mass called a protostar forms at the centre of the cloud. Eventually, the protostar becomes dense and hot enough for nuclear fusion to occur at its centre. It has become a star.

Nuclear fusion causes hydrogen nuclei to fuse together forming helium nuclei. This process releases an enormous amount of energy in the form of electromagnetic radiation. The star is pulled inwards by gravitational attraction. This is balanced by the outward force due to the high temperature in the centre of the star (Figure 22.4). Thus, the star becomes stable.

Eventually, all stars will convert the hydrogen in their centre into helium. What happens next depends on their size. See Figure 22.5.

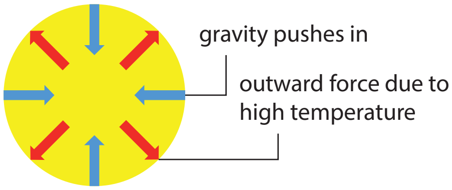


Figure 22.4 *Diagram to show the forces acting inside a stable star*

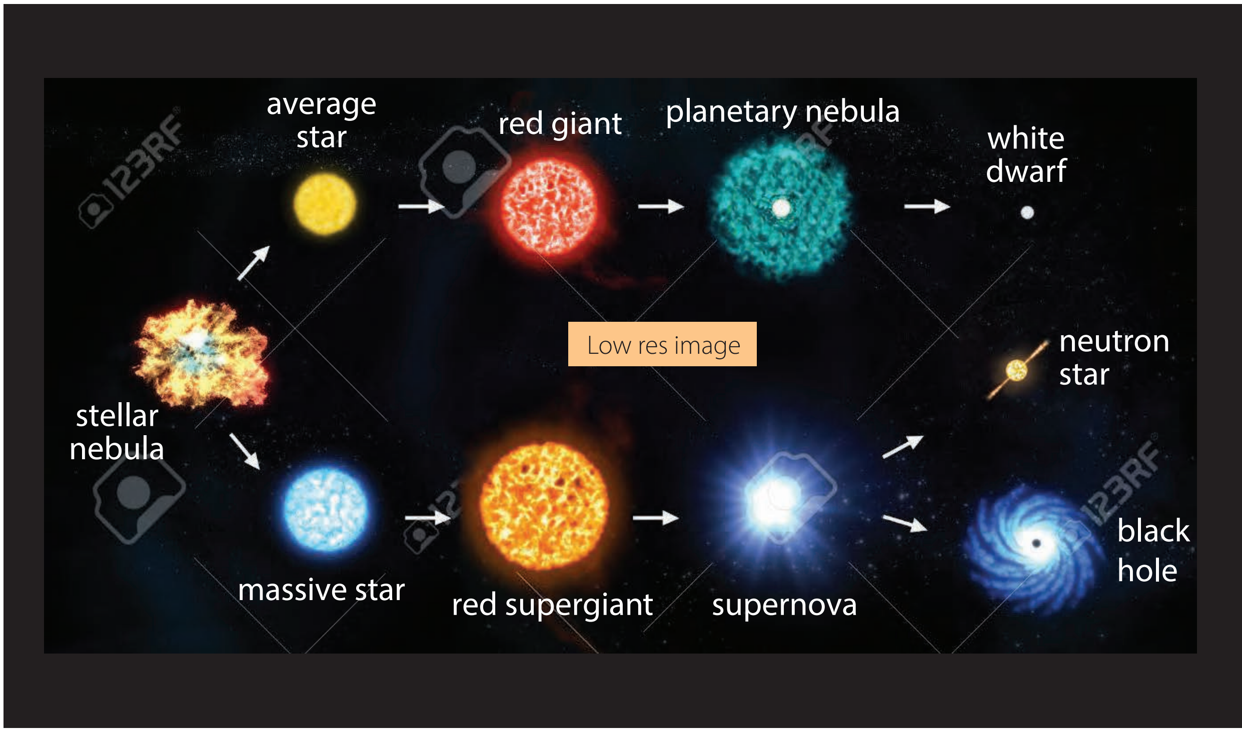


Figure 22.5 *Diagram to show the life of an average star (top row) and a massive star (bottom row)*

Average stars

Most stars are similar to the Sun and remain stable for billions of years. When they run out of hydrogen, nuclear fusion stops. There is no radiation pressure pushing out, so gravity causes the core to collapse and heat up. The collapsing core may be hot enough for some helium nuclei to fuse into carbon and oxygen nuclei. The outer layers expand and cool, turning the star into a **red giant**. Our Sun will probably swell enough to reach the orbit of the Earth.

Eventually, the outer layers are pushed away from the star to become a **planetary nebula**. The central core remains as a **white dwarf** which gradually cools.

Massive stars

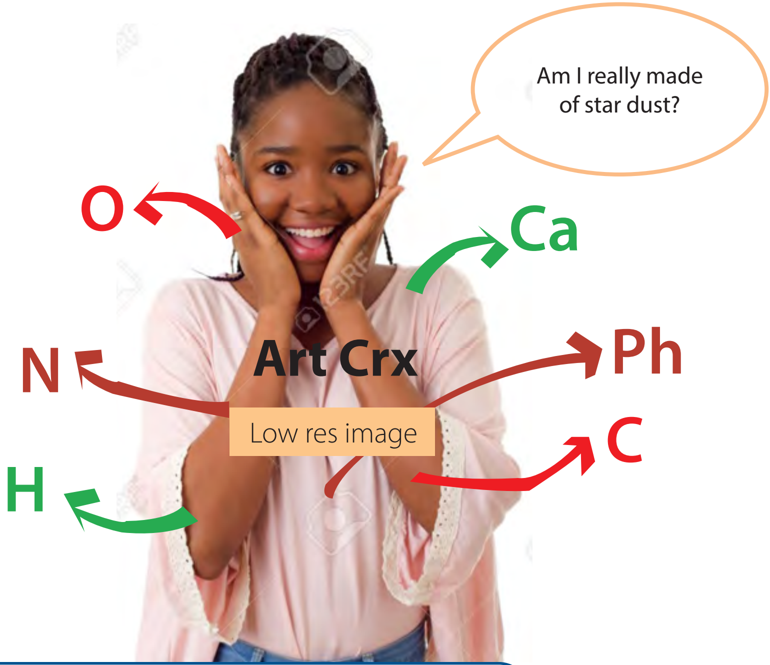
Blue **supergiants** are massive stars that are at least eight times the mass of the Sun. They are hotter and do not live as long as less massive stars. Supergiants live for millions not billions of years.

As with average stars, when the hydrogen is used up, the core shrinks and becomes hotter. The outer layers expand and turn the star into a **red supergiant**. In the core helium, nuclei fuse into more massive nuclei, such as carbon, neon, oxygen and silicon. This releases more energy.

Nuclear fusion stops when nuclei of iron are formed. The star quickly collapses then explodes violently. The explosion is called a **supernova**. There is enough energy in a supernova to produce nuclei more massive than iron. A nebula containing the remaining hydrogen and the new elements expands into space. The nebula may eventually form new stars and planets.

The core of the supernova can be a very dense **neutron star**, which is made of tightly packed neutrons. If it is very massive, it can also be a **black hole**, which is so dense that light cannot escape from it.

What elements are you made of? Almost 99% of the mass of the human body is made up of six elements: oxygen, carbon, hydrogen, nitrogen, calcium, and phosphorus. You have seen how the elements heavier than hydrogen were made inside stars. You really are made of stardust!



HELPFUL NOTES

The term 'planetary' nebula is misleading. It has nothing to do with planets. Astronomers thought they were looking at giant planets. But it is just the glowing shell of gas blown away from the remains of a star.

Let's Practise 22.2

1 Explain what the following terms mean:
(a) billion (b) Milky Way (c) nuclear fusion (d) light-year

2 What names are given to the following descriptions?
(a) An average star that has used up its hydrogen, expanded and cooled
(b) The cloud of gas that has blown away from a dying star
(c) An exploding massive star
(d) The cooling remains of an average star

3 Put this list in order to describe the stages in the life cycle of a massive star.
black hole, massive star, nebula, protostar, red supergiant, supernova

4 What is the length of a light-year in metres?

5 What happens to the forces inside a star when the hydrogen in its core is used up? What will happen to the star?

6 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

LINK

Exercise 22B, pp. XX–XX

22.3 The Universe

In this section, you will learn the following:

- Know the Milky Way as one of many billions of galaxies in the Universe and that it has an approximate diameter of 100 000 light years.
- Describe what is meant by *redshift*.
- Know that the light emitted from stars in distant galaxies appears redshifted compared to light emitted on the Earth.
- Know that redshift is evidence that the Universe is expanding and supports the Big Bang Theory.
- S Know what cosmic microwave background radiation (CMBR) is.
- S Explain that the CMBR was produced shortly after the Universe was formed and that this radiation has been expanded into the microwave region of the electromagnetic spectrum as the Universe expanded.
- S Know how the speed v at which a galaxy is moving away from the Earth can be found.
- S Know how the distance d of a far galaxy can be determined.
- S Define the *Hubble constant* H_0; recall and use the equation $H_0 = \frac{v}{d}$.
- S Know that the current estimate for H_0 is 2.2×10^{-18} per second.
- S Know what the equation $\frac{d}{v} = \frac{1}{H_0}$ represents.

What does the Universe consist of?

In the early 1900s, astronomers believed that the Milky Way was the whole Universe. They saw that it contained fuzzy spirals and thought that these were nebulae.

In 1919, an American astronomer, Edwin Hubble, used a powerful telescope to look at one of these nebulae. He saw that it contained bright stars just like the Milky Way. The fuzzy spirals were actually galaxies more distant than the Milky Way. The diameter of the Milky Way is approximately 100 000 light-years. The *nearest* galaxy to the Milky Way is over 25 000 light-years away from it.

Just as a galaxy contains billions of stars, the Universe contains billions of galaxies. The Universe was much, much larger than anyone had imagined!

ENRICHMENT THINK

1 The Andromeda galaxy is 2.2 million ly from the Earth. How long does it take light from this galaxy to reach the Earth?

2 Explain why looking at the night sky is looking back in time.

What is redshift?

You are probably aware of the Doppler effect (Figure 22.6). When an ambulance approaches, its siren sounds higher and when it moves away it sounds lower.

PHYSICS WATCH

Scan this page to watch a clip of an ambulance demonstrating the Doppler effect.

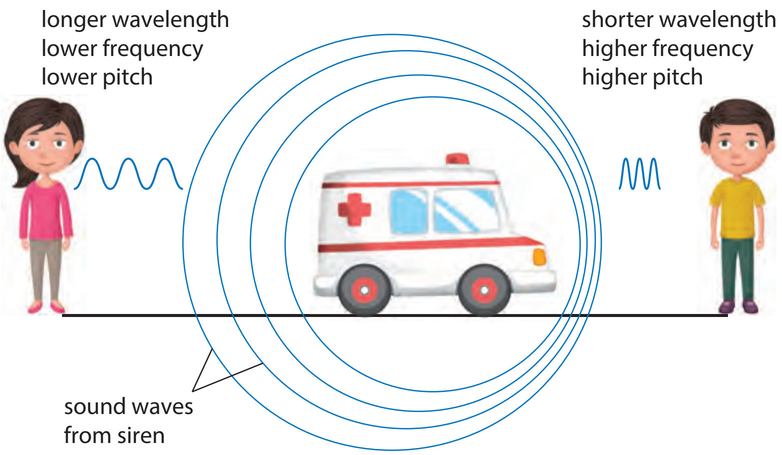


Figure 22.6 *The Doppler effect for sound waves*

This happens because the wavefronts of the sound become closer together when the sound is travelling in the same direction as the ambulance. A shorter wavelength means a higher frequency. When the ambulance moves away, the wavelength is longer so the frequency is lower.

The same thing happens with light sources. When a light source moves towards an observer, the light has a higher frequency. When it moves away, the light has a lower frequency. A higher frequency light would be bluer. It is said to be **blueshifted**. A lower frequency light is redder or **redshifted**.

In Figure 22.7, the top coloured band shows the spectrum of colours from the Sun's light. The black lines show colours that have been absorbed by gases around the Sun.

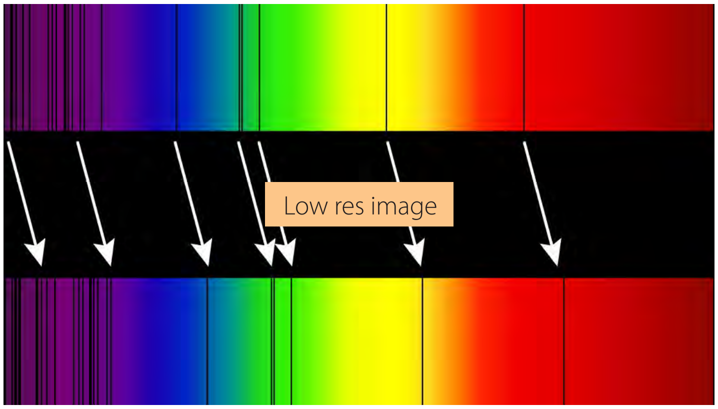


Figure 22.7 *Redshift of spectral lines in light from a distant galaxy*

The bottom coloured band shows the spectrum of colours from a distant galaxy. The white arrows show how the same pattern of black absorption lines have been shifted towards the red end of the spectrum.

What does this tell you about the movement of the distant galaxy? A redshift means the frequency is lower, so the distant galaxy is moving away from Earth.

Redshift is the increase in the observed wavelength of electromagnetic radiation emitted from stars and galaxies which are moving away from the Earth.

Astronomers found that the distant galaxies they can see in the Universe are moving away from the Milky Way galaxy in a similar way. It seems that the whole Universe is expanding.

But what if we imagined time going backwards? Then the galaxies would be moving closer and closer together to a single point. At some moment in the past, all of the matter in the Universe must have exploded outwards from this point and it is still expanding. This is known as the **Big Bang Theory** of the Universe.

ENRICHMENT *ACTIVITY*

You can make a two-dimensional model with a round balloon to show the effect of expansion.

Draw some galaxies on sticky paper and attach them to the balloon. Mark one of them with a cross to be the Milky Way.

Figure 22.8 *Demonstration of expansion of the Universe*

Blow up the balloon. What happens to the distances between the Milky Way and the other galaxies?

What happens to the distances between all the other galaxies?

You will see that the space between all of the galaxies is increasing and they are all moving apart from each other.

Is there more evidence for the Big Bang Theory?

After the Big Bang, the Universe would have been very hot and filled with short wavelength gamma radiation. Expansion of the Universe would cause the wavelength of this radiation to stretch into longer wavelength microwaves.

If the Big Bang theory is correct, the Universe should now be filled with microwaves. These microwaves are called the **cosmic microwave background radiation** or **CMBR**. A race began where scientists competed to build a microwave detector to see if CMBR existed.

A few years later, the CMBR was discovered by accident. Two scientists were testing a microwave receiver they had built for their own research. They found that it always picked up an unwanted background signal of microwaves of wavelength 2 mm. The two scientists thought that it was faulty. Eventually, they learnt about CMBR from a colleague. This led them to realise that what their receiver had found was CMBR.

ENRICHMENT *INFO*

Discovery of CMBR

Penzias and Wilson were the two scientists who were testing the microwave detector. They first thought that the unwanted signal was from pigeons that were nesting in the antenna. They removed the pigeons and their nest, but the signal was still there. They later realised that their detector had found the microwave radiation left behind from the Big Bang.

How old is the Universe?

Edwin Hubble used a powerful telescope (Figure 22.9) to measure the distance of galaxies from the Earth by using their brightness.

By measuring the redshift of starlight from the galaxies, the speed of the galaxy can be calculated.

Hubble found that the more distant galaxies had greater redshifts than the ones that were closer to the Earth. What does this mean?

Light from more distant galaxies has a greater redshift because they are moving away faster. He plotted a graph of the speed against their distance from the Earth and got results similar to the graph shown in Figure 22.10.

The graph in Figure 22.10 shows that the speed v is proportional to the distance d, i.e. $v \propto d$. This is known as *Hubble's law*. The constant of proportionality is known as the *Hubble constant*, H_0.

The **Hubble constant H_0** is defined as the ratio of the speed at which the galaxy is moving away from the Earth to its distance from the Earth.

$$H_0 = \frac{v}{d}$$ where H_0 = Hubble constant

v = speed of movement away from the Earth

d = distance from the Earth

Figure 22.9 *This is the telescope used by Edwin Hubble to measure the distance of galaxies from the Earth.*

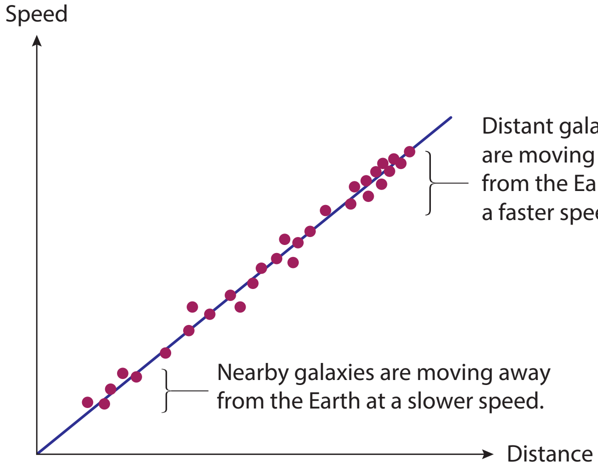


Figure 22.10 *A graph of Hubble's results*

ENRICHMENT *INFO*

To recede means to move away from. The velocity with which the galaxies are moving apart is called their *recessional velocity*.

Astronomers have repeated Hubble's measurements to get a more accurate measurement of the Hubble constant. They have been able to use the space telescope named after him to do this (Figure 22.11).

Figure 22.11 *Hubble space telescope orbiting above the Earth*

For very distant galaxies, astronomers have to look for exploding white dwarf stars. These supernovae produce enough energy to be seen from the Earth. They are thought to give out a known amount of light. The faint light that arrives on the Earth can then be used to estimate their distance away.

The current estimate of H_0 is **2.2 × 10^{-18} per second**.

A reason for getting an accurate value of the Hubble constant is that it can tell us how old the Universe is.

Since average speed v is given by the equation: $v = \frac{\text{distance travelled}}{\text{time}}$

Rearranging this gives: time $t = \frac{\text{distance travelled}}{\text{average speed}} = \frac{d}{v}$

From Hubble's graph, $H_0 = \frac{v}{d}$

$\therefore\ t = \frac{d}{v} = \frac{1}{H_0}$

So $\frac{1}{H_0}$ gives an estimate of the time from the Big Bang or the age of the Universe.

Using the current estimate, this gives:

$t = \frac{1}{2.2} \times 10^{-18}\ \text{s} = 4.5 \times 10^{17}\ \text{s}$ or 14 billion years

WORD ALERT

Supernovae: plural of *supernova*

Let's Practise 22.3

1 Explain why astronomers were shocked to find out that the fuzzy 'nebulae' in the Milky Way were in fact distant galaxies.

2 Which of the following is **correct**?

A The Universe consists of billions of stars.

B The Universe consists of millions of stars.

C The Universe consists of billions of galaxies.

D The Universe consists of millions of galaxies.

3 Explain what is meant by

(a) the Doppler effect;

(b) redshift.

4 **(a)** S What is meant by the *Big Bang Theory*?

(b) What two pieces of evidence support the Big Bang Theory?

5 S Explain what *Hubble's constant* is.

6 **Mind Map** Construct your own mind map for the concepts that you have learnt in this section.

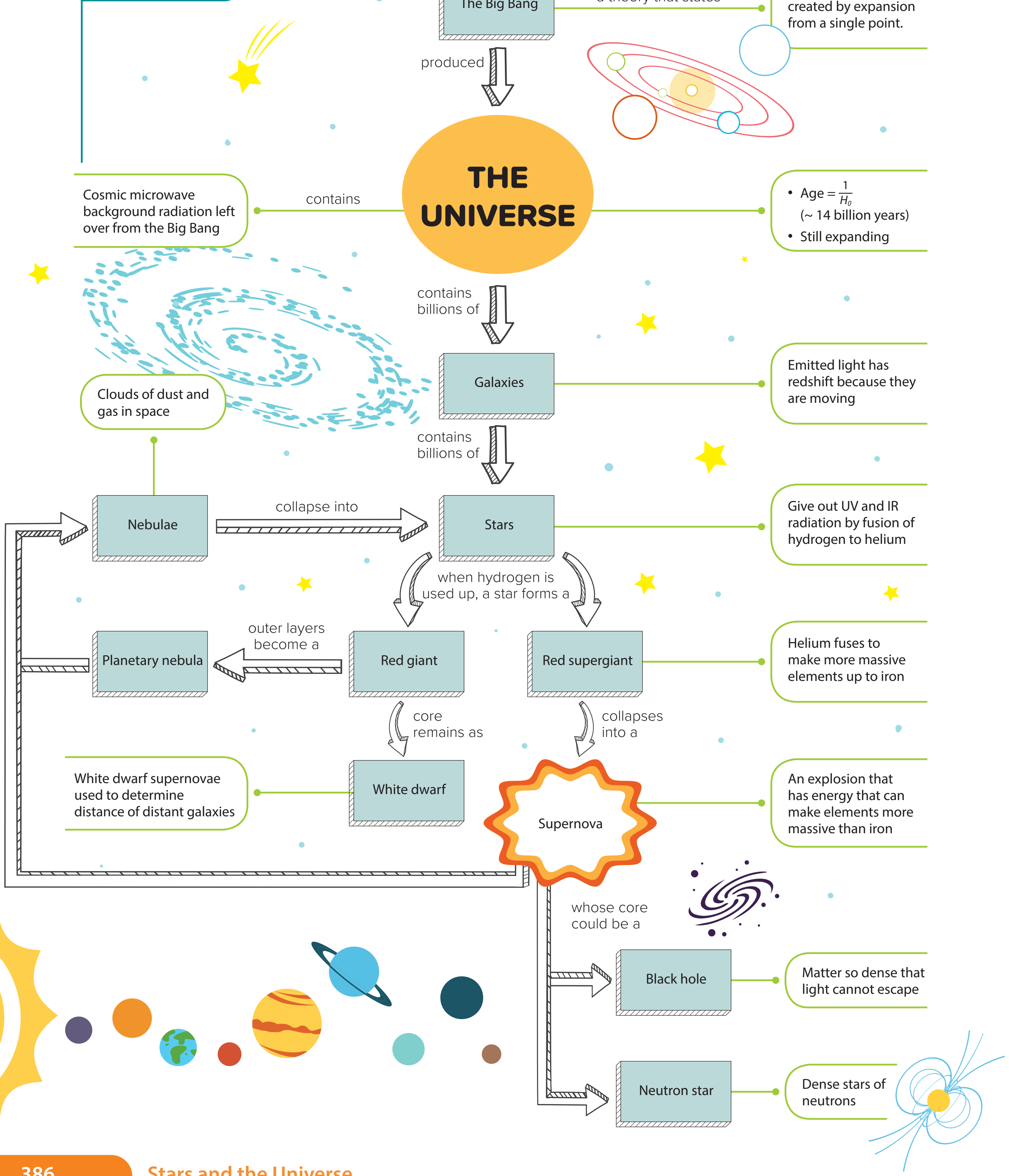
LINK

TWB

Exercise 22C–D, pp. XX–XX

Exercise 22E Let's Reflect, p. X

Let's Map It



The Big Bang
a theory that states
The Universe was created by expansion from a single point.
produced
THE UNIVERSE
contains
Cosmic microwave background radiation left over from the Big Bang
• Age = $\frac{1}{H_0}$ (~ 14 billion years)
• Still expanding
contains billions of
Galaxies
Emitted light has redshift because they are moving
contains billions of
Clouds of dust and gas in space
Nebulae
collapse into
Stars
Give out UV and IR radiation by fusion of hydrogen to helium
when hydrogen is used up, a star forms a
Red giant
Red supergiant
outer layers become a
Planetary nebula
Helium fuses to make more massive elements up to iron
core remains as
White dwarf
collapses into a
Supernova
White dwarf supernovae used to determine distance of distant galaxies
An explosion that has energy that can make elements more massive than iron
whose core could be a
Black hole
Matter so dense that light cannot escape
Neutron star
Dense stars of neutrons

Let's Review

Section A: Multiple-choice Questions

1 Which statement is **correct**?

A A galaxy is a group of millions of stars.
B Large stars live longer than small stars.
C Elements heavier than iron are formed in supernovae.
D A light-year is a unit for measuring time.

2 Which of the following gives the **correct** order of size from largest to smallest?

A Milky Way, Universe, Sun, Jupiter
B Sun, Universe, Jupiter, Milky Way
C Jupiter, Sun, Milky Way, Universe
D Universe, Milky Way, Sun, Jupiter

Section B: Short-answer and Structured Questions

1 S Describe **three** similarities and **three** differences between the life cycle of an average star like the Sun and the life cycle of a massive star.

2 S The astronomer Hubble plotted a graph of the speed with which galaxies were moving away from the Earth against the distance of the galaxies from the Earth.

(a) Explain how he could measure the speed.

(b) Use the axes in Figure 22.12 and sketch the graph he obtained from his results.

Figure 22.12

(c) Explain how the age of the Universe can be estimated from the graph.

3 Figure 22.13 shows Andromeda, a spiral galaxy outside the Milky Way.

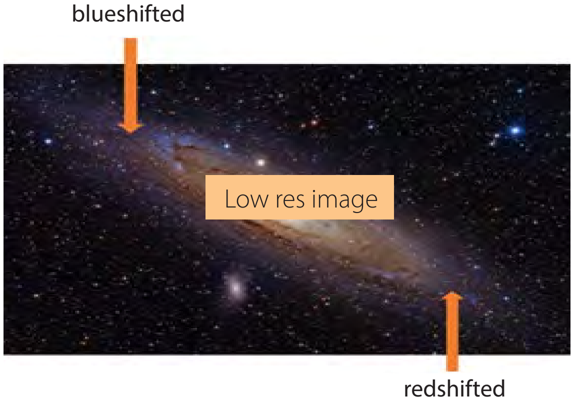


Figure 22.13

When the light from the galaxy was observed on the Earth, light from the left hand side was found to be blueshifted while light from the right hand side was found to be redshifted.

(a) What does this tell you about the movement of each end of the galaxy?

(b) Suggest a reason for this.

Notes to Physics Practical Work

Introduction

For meaningful inquiry-based learning of physics to occur, it is important that students should not just learn physics as a body of facts, models, and theories. Rather, they must also learn physics as an 'empirical' subject, which involves the use of observations and experiments for knowledge construction.

Based on the IGCSE syllabus by CAIE, practical work helps students to:

- use equipment and materials accurately and safely
- develop observational and problem-solving skills
- develop a deeper understanding of the syllabus topics and the scientific approach
- appreciate how scientific theories are developed and tested
- transfer the experimental skills acquired to unfamiliar contexts
- develop positive scientific attitudes such as objectivity, integrity, cooperation, enquiry and inventiveness
- develop an interest and enjoyment in science

[Taken from CAIE Syllabus Cambridge IGCSE Physics 0625]

This section will provide students with notes on:

- some common experimental contexts in practical work
- the safety pointers when performing experiments in the laboratory work
- the practical skills before engaging in the planning of experiments and investigations

Common Experimental Contexts

During experiments, the accurate measurement of physical quantities using instruments is a fundamental skill in practical work. Lord Kelvin (1824–1907), an eminent British scientist, once said, "When you can measure what you are speaking about, and express it in numbers, you know something about it, but when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind: it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter may be."

Below are some notes to some common experimental contexts in physics practical work.

1 General Physics

Common Experimental Contexts	Common Instruments	Link to Chapters
Measuring physical quantities such as length, time, mass and volume	1. Metre rule (length) 2. Vernier calipers (length) 3. Stopwatch (time) 4. Beam balance (mass) 5. Electronic balance (mass) 6. Measuring cylinder (volume) 7. Displacement can (volume) 8. Burette (volume)	Chapter 1 Measurement of Physical Quantities Chapter 3 Mass, Weight and Density
Precautions		
1 Length • Avoid parallax error when using metre rule • Check for zero error when using vernier calipers		

Precautions

2 Time

When timing oscillations, take note of the following points:

- Repeat timings and take the average time for a more accurate measurement.
- To find the period of an oscillation, record the time taken for a large number of oscillations (e.g. 20) and calculate the average time for one oscillation. This average time is more accurate than a direct measurement of the time taken for just one oscillation.
- Ignore the first few oscillations. Start timing only when oscillations are steady and you have gotten used to the rhythm of the oscillation.
- When oscillations become 'abnormal' (e.g. elliptical oscillations in a pendulum), the timing of such oscillations must be ignored.

3 Mass

When you are using the beam balance or an electronic balance, take note of the following points:

- Zero the instrument before use, i.e., set the reading to zero when it is measuring nothing.
- Do not place wet objects on the pan of the scale.
- When weighing chemicals or granular solids, place them in a watch glass (or other suitable containers) of known mass.

4 Volume

- Ensure that your viewing eye is at the same level as the bottom of the meniscus when taking volume readings.

2 Thermal Physics

Common Experimental Contexts	Common Instruments	Link to Chapter
Cooling and heating, including measurement of temperature	1. Thermometer (temperature) 2. Bunsen Burner 3. Beaker 4. Boiling tube 5. Measuring cylinder (volume)	Chapter 9 Thermal Properties and Temperature Chapter 10 Transfer of Thermal Energy

Precautions

1 When using a mercury-in-glass thermometer, take note of the following:

- Avoid using the thermometer as a stirrer.
- Record temperature readings to the smallest half division.
- Avoid parallax errors when taking temperature readings by reading the scale with your line of sight perpendicular to the stem of the thermometer.
- If you are measuring the temperature of a liquid in a container, stir the liquid continuously with a stirrer to ensure that the temperature is uniform throughout the liquid.

2 When using a Bunsen burner, take note of the following:

- Close the air holes completely before lighting the burner. Lighting the burner with open air-holes may result in a "strike back".
- The temperature and the colour of the Bunsen flame is controlled by the size of the air-hole openings. For a very hot blue flame, open the air-hole slowly to allow air to mix with the gas.
- A Bunsen burner that is working properly will not produce a loud noisy hiss.
- If the burner is hissing loudly, turn off the gas supply and check that the jet is not choked. Do not touch the hot collar or barrel with your bare hands.
- The size of the flame can be controlled by adjusting the gas tap.

3 Optics

Common Experimental Contexts	Common Instruments	Link to Chapter
Measuring quantities such as angles of reflection	1. Illuminated object 2. Optical pins 3. Lenses 4. Transparent prisms and blocks 5. Protractor (incident, reflected and refracted angles)	Chapter 12 Light

Precautions

1 When using an illuminated object, ensure that the lights in the lab are switched off or dimmed with the curtains drawn.

2 When using optical pins, take note of the following:
- The two pins used to locate the path of the ray of light must be placed as far apart as possible when they are aligned.
- The pins must be placed vertically upright.

3 When performing experiments involving lenses, note the following points:
- The lens must be upright. If he lens is tilted, the image formed on a vertical screen may not be as sharp as it could be.
- Object and image distances should be measured along a line parallel to the principal axis.
- The centre of the illuminated object and the centre of the screen should be placed near the principal axis of the lens. Both the object and the screen should be positioned at right angles to this axis.

4 When using the protractor, avoid parallax error.

4 Magnetism

Common Experimental Contexts	Common Instruments	Link to Chapter
Finding the magnetic field pattern of a permanent bar magnet	1. Permanent bar magnets 2. Plotting compass	Chapter 15 Simple phenomena of Magnetism

Precautions

1 When handling magnets or plotting compass, remember the following points:
- Do not drop them or knock them unnecessarily.
- Avoid placing them near hot objects, such as a Bunsen burner or a beaker of hot water.

2 When storing magnets, store them in pairs with soft iron keepers when they are not in use.

5 Electricity

Common Experimental Contexts	Common Instruments	Link to Chapter
• Determining a derived quantity such as the value of a known resistance • Testing and identifying the relationship between two variables such as between the potential difference across a wire and its length • Connecting and reconnecting of electric circuits, and measuring of current and potential difference	1. Dry cell 2. Resistor 3. Ammeter 4. Voltmeter 5. Plug-key switch 6. Filament lamp 7. Wire 8. Crocodile clip	Chapter 16 Electrical Quantities Chapter 17 Electrical Circuits and Electrical Safety
Precautions		
1 Avoid parallax error when using the ammeter or voltmeter. 2 Check for zero error when using the ammeter or voltmeter. 3 Minimise heating effects by breaking the circuit using the plug-key switch after taking the readings.		

Safety Pointers

Carrying out any experiment in the laboratory can be dangerous if we do not follow basic safety guidelines. Here are some basic safety pointers that you should be aware of:

Before you begin …

1 Make sure your workbench is not cluttered with unnecessary items (such as your school bag, files, clothes and books). Keep your workbench neat and clean.
2 Read all the instructions in your practical workbook before you do anything.
3 Look out for possible dangers.

While you are conducting the experiment …

1 Follow the instructions in the practical workbook closely. Do not do anything you are not instructed to do without your teacher's permission.
2 Do not fool around and endanger people around you.
3 Wear or use protective devices provided for you. These protective devices include goggles, gloves and safety tongs.
4 Never leave heating apparatus unattended. Turn off Bunsen burners when you have to leave your workbench for a while or when you have completed your experiments.
5 If you have broken any glassware (beakers, test tubes and thermometers, etc.) or spilt any liquids, inform your teacher immediately.
6 Find out where fi re extinguishers are located in the laboratory and how to operate one.

After you have finished the experiment …

1 Clean your workbench.
2 Do not dispose of materials in the sink unless you are instructed to do so.
3 Wash your hands thoroughly.

The pointers above are only some of the important safety guidelines that you should follow to avoid accidents. The best preventive measure is to always be careful and alert. Take care of yourself and your neighbours. Above all, pay attention to your teacher.

Practical Skills

1 Planning an Investigation

Planning an investigation involves the four main steps shown below.

Step	Elaboration
1 Define the problem.	• Make a clear statement of the problem • Identify the independent and the dependent variables. **Example 1: Period of a Simple Pendulum** *Statement of the problem:* What is the relationship between the period and the length of a simple pendulum? *Variables:* (a) Independent variable: length of thread L (b) Dependent variable: time t for 20 oscillations **Example 2: Resistance of a Fixed Resistor** *Statement of the problem:* How to determine the resistance of a fixed resistor using the voltmeter-ammeter method? *Variables:* (a) Independent variable: potential difference V (b) Dependent variable: current I
2 Describe how data is to be collected.	Give a clear and logical account of the experimental procedure, including a description of • how the independent variable is to be varied; • how the independent and the dependent variables are to be measured; • how the other variables are controlled; • the arrangement of the apparatus that will be used.
3 Describe the analysis of the collected data.	Describe how the data collected should be processed to fulfil the purpose of the investigation. **Example 1: Period of a Simple Pendulum** 1. For each value length L and the corresponding time t for 20 oscillations, the period $T = \frac{t}{2}$ is calculated. 2. Plot a graph of T/s (y-axis) against L/cm (axis) to deduce the relationship between the period T and length of L of the pendulum. 3. Conclusion: The period of a pendulum increases with its length. **Example 2: Resistance of a Fixed Resistor** 1. By adjusting the position of the sliding contact on the rheostat, record three pairs of the potential difference V and the current I across the fixed resistor 2. For each pair of V and I, calculate the resistance of the fixed resistor using $R = \frac{V}{I}$ 3. Conclusion: The resistance of a fixed resistor can be determined by finding the average value of the three pairs of R in (2).
4 Think of the relevant safety precautions.	Suggest suitable safety precautions to be taken. **Example 1: Period of a Simple Pendulum** 1. Ensure that the pendulum oscillates steadily in a vertical plane before starting the timing. 2. To find the period of an oscillation, record the time taken for a large number of oscillations (e.g. 20) and calculate the average time for one oscillation. **Example 2: Resistance of a Fixed Resistor** 1. Check for zero error when using the ammeter or voltmeter. 2. Minimise heating effects by breaking the circuit using the plug-key switch after taking the readings of V and I.

2 Displaying Data on Graphs

Graphs are plotted to show the relationship between two quantities. The quantity that you choose to vary (independent variable) is usually plotted on the x -axis. You should vary this quantity in nearly regular intervals covering the entire range of the quantity available in the experiment. The quantity that is dependent on the quantity that you vary (dependent variable) is plotted on the y -axis.

The following points should be noted when drawing graphs:

1 Both axes should be labelled in this manner: name of quantity/unit, e.g., time/second, time/s or t/s.
2 Use a convenient scale to draw the graph as large as the available space allows.
3 Avoid using awkward scales such as 2 cm : 3 units. Such scales usually lead to errors in plotting and deduction.
4 Points must be clearly and accurately marked with small, sharp crosses (×).
5 Do not attempt to join all the plotted points on the graph. It is not likely that you will obtain a straight line or a smooth curve by joining all the points, as there are bound to be errors in the experimental readings. Instead, use a long (30 cm) transparent ruler to help you draw the best straight line, or a flexible curve ruler to draw a smooth curve. Remember to use a sharp pencil to draw the straight line or curve.
6 The best straight line (Figure 1) or the best smooth curve (Figure 2)
   (a) passes through the middle of the spaces between the points;
   (b) has about the same number of points on either side of the line over
   (c) its entire length;
   (d) does not necessarily pass through any plotted points or the origin.
7 For an irregular point that is far from the best straight line or curve, either
   (a) repeat the measurement and/or calculations for the point and correct it. OR
   (b) circle the point and indicate that the point has been rejected and ignored.
8 The gradient of a straight line should be calculated from a right-angled triangle drawn with dotted lines. The hypotenuse should be as long as possible, and no shorter than half of the straight-line graph. The ends of the hypotenuse must not be any of the plotted points.
9 Draw dotted lines to find a point on the x -axis corresponding to a point on the y -axis, and vice versa.

Figures 1 to 10 show examples of desirable and undesirable graphs.

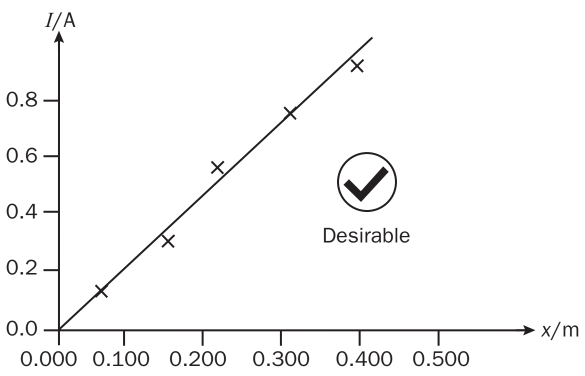


Figure 1

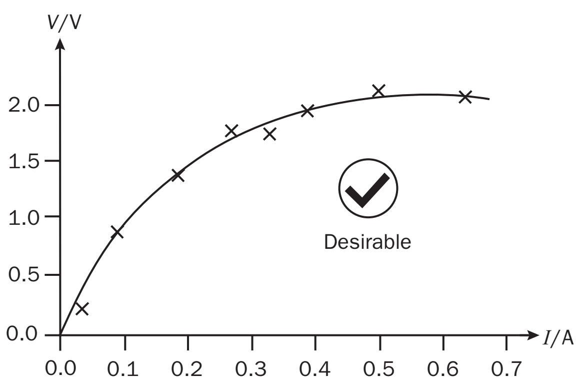


Figure 2

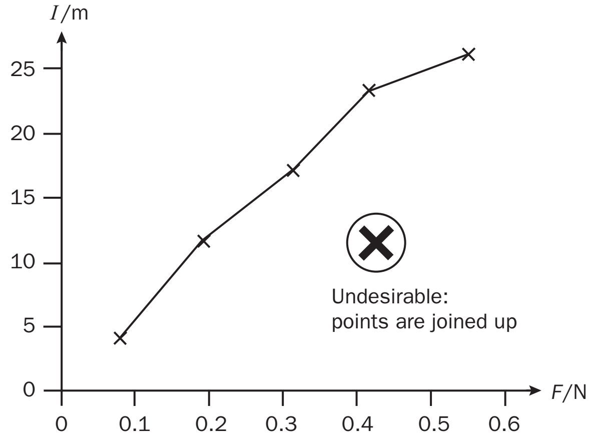


Figure 3

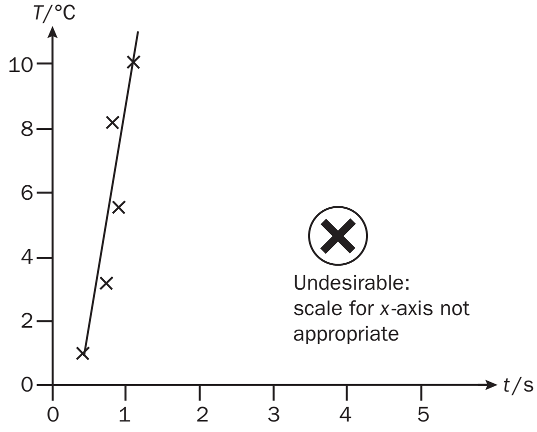


Figure 4

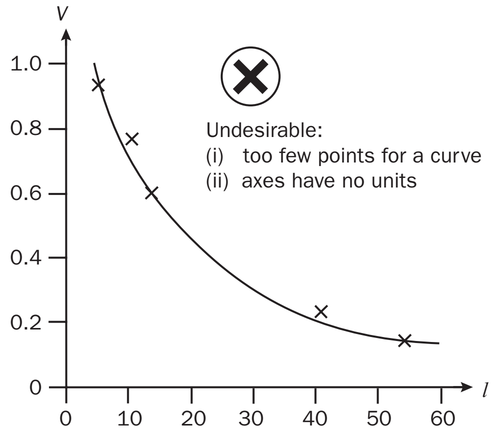


Figure 5

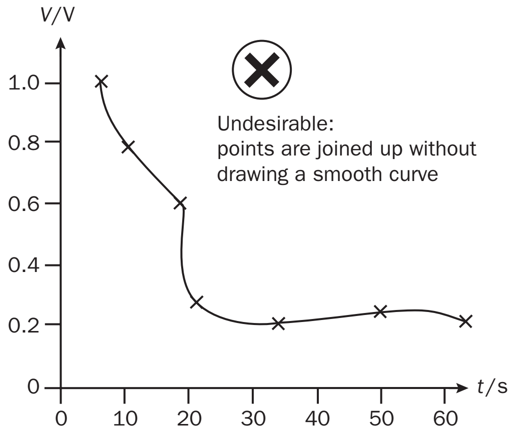


Figure 6

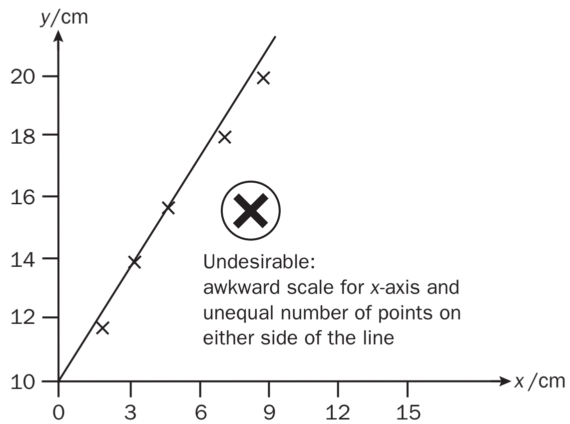


Figure 7

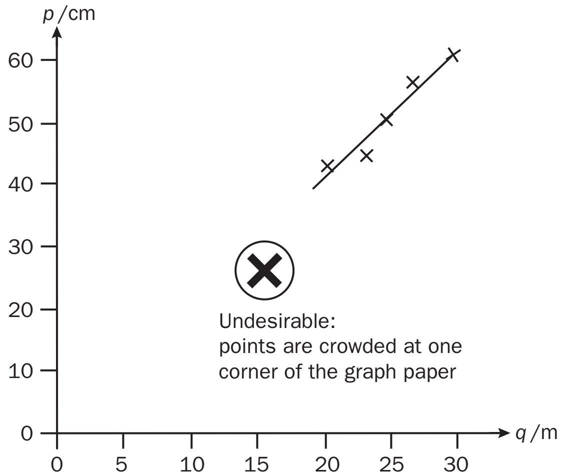


Figure 8

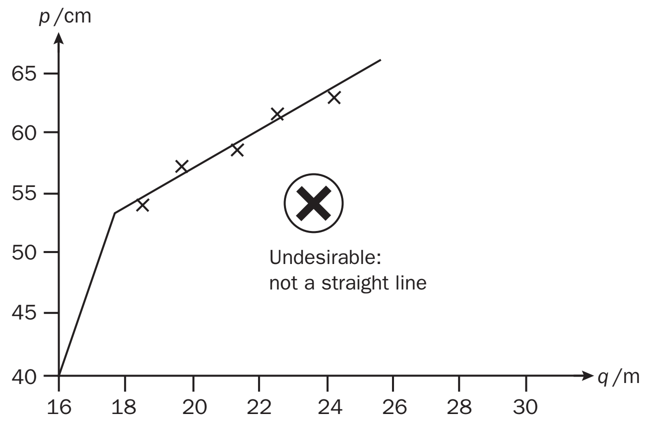


Figure 9

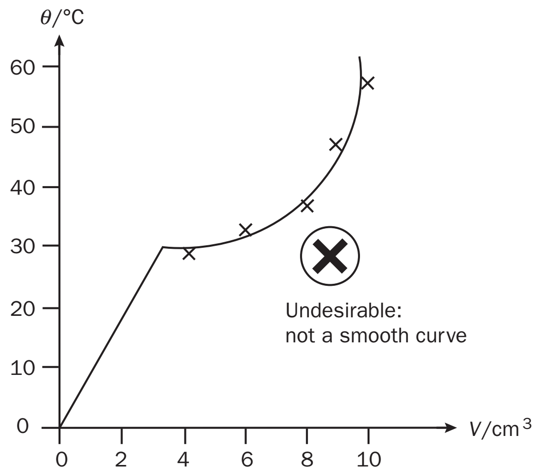


Figure 10

3 Interpreting Graphs

After you have gathered your data in an experiment, you may wish to know how two variables are related to each other. One simple way of examining the mathematical relationship between two variables is to plot a graph. The graph will indicate the general trend of the mathematical relationship between the two variables.

At the level of this course, there are two common mathematical relationships that you may encounter. If x and y are the variables that you are investigating, the two mathematical relationships are:

(a) $y = kx$ (y is directly proportional to x; k = constant);

(b) $y = \frac{k}{x}$ (y is inversely proportional to x; k = constant).

Figure 11 shows a $y = kx$ relationship. Notice that in this relationship,

- when x increases to $2x$, y increases by the same factor of 2;
- when x decreases to $\frac{1}{2}x$, y decreases by the same factor of $\frac{1}{2}$.

In this relationship, we say that y is (directly) **proportional** to x.

You may encounter some cases in which y is inversely proportional to x, i.e. $y = \frac{k}{x}$.

In such cases, the graph of y against x is a curve, which makes it difficult for us to determine the constant k. We will obtain a straight-line graph when we plot y against $1x$ instead of x.

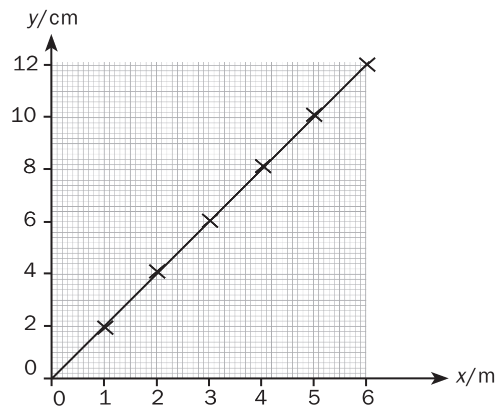


Figure 11

Quick Revision Guide

Chapter 1: Measurement of Physical Quantities

- A **physical quantity** is a quantity that can be measured. It consists of a numerical magnitude and a unit.
- **SI units** are the units of measurement in the widely used International System of Units.
- The smallest unit an instrument can measure is known as its **precision.**
- When using a metre rule, if eye level is not positioned perpendicularly to the rule, **parallax error** will be introduced.
- Taking several readings and calculating the **average** also minimises errors.
- When using the vernier calipers, we need to examine the instrument for zero error. This occurs when the zero marks on the two scales of the vernier calipers do not coincide.
- We can tell time by observing events that repeat at **regular intervals** or **periods**.
- Each complete to-and-fro motion is one oscillation.
- The **period** of a simple pendulum is the time taken for one complete oscillation.
- S A **scalar quantity** is a physical quantity that has **magnitude only.**
- S A **vector quantity** is a physical quantity that has both **magnitude and direction.**
- In a vector diagram, a vector quantity is represented by an arrow. The length of the arrow is proportional to the magnitude of the vector. The direction of the arrow indicates the direction of the vector.
- The single vector, called the **resultant vector**, must be equivalent to the individual vectors combined in terms of magnitude and direction.

Chapter 2: Motion

- **Speed** is the distance travelled per unit time.
- **Speed** $= \dfrac{\textbf{distance travelled}}{\textbf{time taken}}$
- **Average speed** $= \dfrac{\textbf{total distance travelled}}{\textbf{total time taken}}$
- **Distance** is the total length covered by a moving object regardless of the direction of motion.
- **Displacement** is the distance measured in a straight line in a specified direction.
- **Velocity** is speed in a given direction.
- **Velocity** $= \dfrac{\textbf{displacement}}{\textbf{time taken}}$
- S **Acceleration** is the change of velocity per unit time.
- **Acceleration,** $\boldsymbol{a} = \dfrac{\textbf{change of velocity}}{\textbf{time}} = \dfrac{\Delta v}{\Delta t}$
- The gradient of a distance–time graph of an object gives the speed of the object.
- The area under a speed–time graph gives the distance travelled.
- S The gradient of a speed–time graph gives the acceleration of the object.
- **Acceleration due to gravity**, **g**, is a constant for objects close to the Earth's surface.
- An object can only be in **free fall** if the only force acting on it is its own weight.
- **Air resistance** is a form of frictional force.
- An object falling through air achieves a uniform velocity known as **terminal velocity** when its weight is equal to the air resistance against it.

Chapter 3: Mass, Weight and Density

- **Mass** is a measure of the quantity of matter in an object at rest relative to the observer.
- **Weight** is the gravitational force on an object that has mass.
- A **gravitational field** is a region of space in which a mass exerts a force of attraction on another mass.
- S The weight of an object is the effect of a gravitational field on a mass.
- **Gravitational field strength *g*** is defined as the gravitational force per unit mass.

  $\boldsymbol{g} = \dfrac{\boldsymbol{W}}{\boldsymbol{m}}$ *where* *g = gravitational field strength (in N/kg)*
  W = weight (in N)
  m = mass of the object (in kg)
- The **density** of a substance is defined as its mass per unit volume.

  $\boldsymbol{\rho} = \dfrac{\boldsymbol{m}}{\boldsymbol{V}}$ *where* ρ = density
  m = mass of the object
  V = volume of the object

Chapter 4: Forces

- Forces can change the size and shape of an object. They can change the motion of an object.
- We can plot the **load-extension graph** to show the relationship between the force and the extension of an elastic solid.
- S The **spring constant** is defined as the force per unit extension.

  $\boldsymbol{k} = \dfrac{\boldsymbol{F}}{\boldsymbol{x}}$ where k = spring constant
  F = force
  x = extension
- S There is a point beyond which the extension is no longer directly proportional to the load. This point is called the **limit of proportionality**.
- A force is a vector quantity with both magnitude and direction. When more than one force acts on an object, we need to consider the direction of each force in order to determine the **resultant force**.
- A resultant force may change the velocity of an object by changing its direction of motion or its speed.
- An object either remains at rest or continues in a straight line at constant speed unless acted on by a resultant force.
- The resultant force F acting on an object of mass m is related to the acceleration of the object by the following equation:

  $\boldsymbol{F = ma}$ where F = force (in N)
  m = mass (in kg)
  a = acceleration (in m/s^2)
- **Friction** is a force that impedes motion. It is a resistive force because it acts in the opposite direction to motion.
- Friction between two moving surfaces produces heating.
- **Moment of a force** is defined as the product of the force and the perpendicular distance from the pivot.

  Moment of a force $= \boldsymbol{F \times d}$
  where F = force (in N)
  d = perpendicular distance from the pivot (in m)

- When the total clockwise moment is equal to the total anticlockwise moment, there is no resultant turning effect about a pivot. This is the **principle of moments**.
- When there is no resultant force and no resultant moment, an object is in **equilibrium**.
- The **centre of gravity** of an object is the point through which the weight of the object acts.
- To increase the stability of an object, its centre of gravity should be kept as low as possible and its base area should be kept as wide as possible.

Chapter 5: Momentum

- S **Momentum** is defined as the product of mass and velocity.
- **Momentum = mass × velocity**

  $p = mv$ where p = momentum
  m = mass
  v = velocity
- S **Impulse** is the product of force and the period of time for which force acts.
- S **Impulse = force × time =** $F\Delta t$
- S **Resultant force** on an object is the change in momentum per unit time.

  $$F = \frac{\Delta p}{\Delta t}$$
- S The **principle of conservation of momentum** states that the total momentum of two objects just before collision is the same as the total momentum of the objects immediately after the collision.

Chapter 6: Energy, Work and Power

- **Energy** is the capacity to do work.
- Energy may be stored as kinetic energy, gravitational potential energy, chemical energy, elastic (strain) energy, nuclear energy, electrostatic energy and internal (thermal) energy.
- S Kinetic energy can be calculated using

  $E_k = \frac{1}{2}mv^2$ where E_k = kinetic energy (in J)
  m = mass of the body (in kg)
  v = speed of the body (in m/s)
- S **Gravitational potential energy** can be calculated using

  $\Delta E_p = mg\Delta h$ where E_p = gravitational potential energy (in J)
  m = mass of the body (in kg)
  g = gravitational field strength (in N/kg)
  h = height (in m)
- The **principle of conservation of energy** states that energy cannot be created or destroyed. It can be converted from one form to another or transferred from one body to another. The total amount of energy remains constant.
- Energy conversions taking place can be shown using a **flow diagram**.
- S A **Sankey diagram** can be used to represent the energy conversions involving multiple stages.
- **Work done** by a constant force on an object is the product of the force and the distance moved by the object in the direction of the force.

  $W = F \times s$ where W = work done by a constant force F (in J)
  F = constant force (in N)
  s = distance moved by the object in the direction of the force (in m)
- We can obtain energy from fossil fuels, biofuels, hydropower, geothermal energy, solar energy and nuclear energy.
- S The Sun is our main source of energy for all our energy resources except for geothermal, nuclear and tidal resources.
- S The efficiency of a machine can be calculated using:

  $$\textbf{Efficiency} = \frac{\textbf{useful energy output}}{\textbf{energy input}} \times 100\%$$

  $$\textbf{Efficiency} = \frac{\textbf{useful power output}}{\textbf{power input}} \times 100\%$$
- **Power** is defined as the work done or energy transferred per unit time.

  $P = \frac{W}{t} = \frac{\Delta E}{\Delta t}$ where P = power (W)
  W = work done (J)
  ΔE = energy converted (J)
  t = time taken (s)

Chapter 7: Pressure

- **Pressure** is defined as force per unit area.

  $p = \frac{F}{A}$ where p = pressure (in Pa)
  F = force (in N)
  A = area (in m^2)
- S The change in pressure in a liquid is given by

  $\Delta p = \rho g \Delta h$ where p = pressure (in Pa)
  ρ = density (in kg/m^3)
  g = gravitational field strength (in N/kg)
  Δh = depth (in m)

Chapter 8: Kinetic Particle Model of Matter

- When a solid is heated, it **melts** into a liquid at its **melting point**. A liquid that is heated will **boil** and become a gas at its **boiling point.** When a gas is cooled to its boiling point, it will **condense** into a liquid. A liquid will **freeze/solidify** into a solid when cooled to its melting point.
- S The forces and distances between particles affects the properties of solids, liquids and gases.
- The **kinetic particle model of matter** states that the tiny particles that make up matter are always in continuous random motion.
- The lowest temperature where the particles have the least kinetic energy occurs at **–273°C**. This temperature is also known as **absolute zero.**
- **Brownian motion** refers to the *random movement* of microscopic particles in a fluid due to the collisions by the molecules of the fluid.
- The gas pressure of a gas at fixed volume and mass increases with temperature.
- The gas pressure of a fixed mass of gas at constant temperature increases when the volume decreases.
- S The decrease in the volume resulting in a proportional increase in pressure is known as **inverse proportionality**.
- For an inverse proportionality,

  $p \; a \; \frac{1}{V}$ or $p = \frac{k}{V}$ where p = pressure
  k = proportionality constant
  V = volume
- Temperature can also be measured using kelvin, K, which is the SI unit for temperature. The **Kelvin scale** of temperature has absolute zero as 0 kelvin, or 0K.
- To convert a temperature (θ) measured in °C into a temperature (T) in K:
- **T (in K) =** θ **(in °C) + 273**

Chapter 9: Thermal Properties and Temperature

- Solids, liquids and gases increase in volume or expand when heated. The greater the temperature rise, the greater the expansion. When cooled, the volume will decrease, i.e., it will contract.
- Liquids expand more than solids for the same temperature rise.
- Gases expand much more than liquids.
- The **internal energy** of a substance is the total energy of all of its particles.
- The higher the temperature of a substance (measured in °C or K), the greater the internal energy of the substance (measured in J).
- S **Specific heat capacity** c is defined as the amount of thermal energy required to raise the temperature of a unit mass (e.g. 1 kg) of a substance by 1°C (or 1 K).

  $\boldsymbol{c = \frac{\Delta E}{m\Delta\theta}}$ where ΔE = thermal energy required (in J)
  $\Delta\theta$ = temperature change (in K or °C)
  m = mass of substance (in kg)
- The **melting point of pure water** at standard atmospheric pressure of 1 atmosphere is **0°C**.
- The **boiling point of pure water** at standard atmospheric pressure of 1 atmosphere is **100°C**
- **Evaporation** involves a change of state from liquid to gas.
- Evaporation causes cooling of a liquid.
- S Temperature, surface area and air movement over a surface affect evaporation.

Chapter 10:Transfer of Thermal Energy

- Thermal energy always flows from *a region of higher temperature* to *a region of lower temperature*. Net flow of thermal energy occurs only when there is a *difference in temperature*.
- **Conduction** is the transfer of thermal energy through solids.
- The **thermal conductivity** of a material is dependent on how quickly thermal energy is transferred from the hotter end to the colder end. Materials that can transfer thermal energy quickly are good thermal conductors, while materials that transfer thermal energy slowly are bad thermal conductors or insulators.
- **Convection** is the transfer of thermal energy in a fluid (liquid or gas) by means of convection currents due to a difference in density.
- **Thermal radiation** is the transfer of thermal energy in the form of invisible waves called infrared radiation which can travel through a vacuum.
- The amount of infrared radiation absorbed by or emitted from a surface is dependent on the **colour and texture** of the surface. Dull and black surfaces emit and absorb infrared radiation at a faster rate than shiny and silver surfaces. Shiny and silver surfaces reflect more infrared radiation.
- The higher the **surface temperature** of an object relative to the surrounding temperature, the higher the rate of emission of infrared radiation.
- When we compare two objects of the same mass and material, but with different surface areas, the object with the larger **surface area** will emit or absorb infrared radiation at a higher rate.
- The greenhouse effect is a natural process that warms the Earth's surface through a balance of absorption and emission of infrared radiation.

Chapter 11: General Properties of Waves

- **Wave motion** is made up of periodic motion or motion repeated at regular intervals.
- One complete cycle of such motion is known as an **oscillation** or a **vibration**.
- The source of a wave is a vibration or an oscillation.
- Waves transfer energy from one point to another.
- Waves transfer energy without transferring the medium.
- **Transverse waves** are waves that propagate perpendicular to the direction of the vibration.
- **Longitudinal waves** are waves that propagate parallel to the direction of the vibration.
- A **crest** is the highest point of a transverse wave.
- A **trough** is the lowest point of a transverse wave.
- The **amplitude** A of a wave is the maximum displacement of a point from its rest position.
- The **wavelength** λ of a wave is the shortest distance between any two points in phase.
- The **period** T of a wave is the time taken to produce one complete wave.
- The **frequency** f of a wave is the number of complete waves produced per second.
- **Wave speed** v is the distance travelled by a wave per second.

  $\boldsymbol{v = f\lambda}$ where v = wave speed (in m/s)
  λ = wavelength (in m)
  T = period (in s)
- A **wavefront** is an imaginary line on a wave that joins all adjacent points that are in phase.
- When water waves hit a barrier, they undergo **reflection.**
- Waves undergo **refraction** when the they pass from one medium to another.
- S **Diffraction** involves the spreading out of waves when they encounter gaps and edges.

Chapter 12: Light

- **Reflection** is the rebounding of light at a surface.
- **Incident ray** is light ray that hits the reflecting surface.
- **Point of incidence** is the point at which the incident ray hits the reflecting surface.
- **Reflected ray** is light ray that bounces off the reflecting surface.
- **Normal** is the imaginary line perpendicular to the reflecting surface at the point of incidence.
- **Angle of incidence** i is the angle between the incident ray and the normal.
- **Angle of reflection** r is the angle between the reflected ray and the normal.
- The **law of reflection** states that the angle of incidence i is equal to the angle of reflection r (i.e. $i = r$).
- A plane mirror image is of the **same size** as the object, **laterally inverted**, **upright**, **virtual** and **same distance** from the mirror as the object.
- A **real** image can be captured on a screen and the light rays meet at the image position.
- **Refraction** is the bending of light as it passes from one optical medium to another.
- **Angle of refraction** r is the angle between the refracted ray and the normal.
- S The **law of refraction** states that, for two given media, the ratio of the sine of the angle of incidence, i, to the sine of the angle of refraction, r is a constant. This is also known as **Snell's Law**.

  $$\frac{\sin i}{\sin r} = \text{constant}$$
- S The **refractive index** n is the ratio of the speeds of a wave in two different regions.

- $n = \dfrac{\sin i}{\sin r}$ where i = angle of incidence in vacuum
  r = angle of refraction in the medium
- The **critical angle** c is defined as the angle of incidence in an optically denser medium for which the angle of refraction in the optically less dense medium is 90°.
- **Total internal reflection** is the complete reflection of a light ray inside an optically denser medium at its boundary with an optically less dense medium.
- **S** Relationship between the critical angle c and the refractive index n of an optical medium:

  $\sin c = \dfrac{1}{n}$
- A **converging lens** causes light rays to converge to a point. It is *thicker in the centre*.
- A **diverging lens** causes light rays to diverge from a point. It is *thinner in the centre*.
- **Focal length** f is the distance between the optical centre C and the focal point F.
- The **principal axis** is the horizontal line passing through the optical centre of the lens. It is perpendicular to the vertical plane of the lens.
- The **principal focus (or focal point)** is the point at which all rays parallel to the principal axis converge after refraction by the lens. A lens has two focal points, one on each side of the lens.
- The different colours of light observed is called a **spectrum**
- This change in refractive index across the spectrum is known as **dispersion**.
- **S** Any single frequency of light is described as **monochromatic**.

Chapter 13: Electromagnetic Spectrum

- Light from the Sun travels as electromagnetic waves. These waves are of different types and they make up the **electromagnetic spectrum**.
- Waves with higher wavelength have lower frequencies.
- All electromagnetic waves travel at the **same high speed** in a vacuum.
- **S** The speed of electromagnetic waves in a vacuum is $\mathbf{3 \times 10^8}$ **m/s**.
- **S** An **analogue signal** has continuous values in time.
- **S** A **digital signal** has fixed values. For example, it can have two values of 1 and 0.

Chapter 14: Sound

- **Sound** is a form of energy that is transferred from one point to another.
- Sound is produced by **vibrating sources** placed in a medium. The medium is usually air, but it can be any gas, liquid or solid.
- **S** **Compressions** are regions where air pressure is higher than the surrounding air pressure.
- **S** **Rarefactions** are regions where air pressure is lower than the surrounding air pressure.
- For humans, the audible sound range is from **20 Hz to 20 000 Hz**.
- Sound waves need a medium to travel from one point to another.
- **S** In general, sound travels faster in solids than in liquids and faster in liquids than in gases.
- An **echo** is a reflection of sound waves. It is formed when a sound is reflected off hard, flat surfaces.
- **Ultrasound** is sound with a frequency higher than 20 kHz.
- **S** Ultrasound is used in testing materials for quality control, medical scanning and sonar technologies.
- **Pitch** is related to the frequency of a sound wave — the higher the frequency, the higher the pitch.
- **Loudness** is related to the amplitude of a sound wave — the larger the amplitude, the louder the sound.

Chapter 15: Simple Phenomena of Magnetism

- **Magnetic materials** are materials that can be attracted to a magnet.
- **Non-magnetic materials** are materials that cannot be attracted to a magnet.
- Like poles **repel**, unlike poles **attract**.
- The process of magnetising a magnetic material is known as **magnetic induction**. When the magnetic material has become magnetised, we say that it has become an **induced magnet**.
- A **magnetically soft** material can be easily magnetised and also lose its magnetism easily. A **magnetically hard** material is difficult to magnetise, but once magnetised, retains its magnetism afterwards.
- Every magnet has a region of space around it called a **magnetic field.**
- A magnetic material or magnetic pole placed in the magnetic field will experience a force.
- The arrangement of a group of magnetic field lines is called a **magnetic field pattern**.
- The *direction* of the magnetic field lines at a point is the direction of the force on the N pole of a magnet at that point.
- **S** The *relative strength* of a magnetic field is dependent on how closely packed the magnetic field lines are.
- **S** Magnetic forces are due to interactions between magnetic fields.

Chapter 16: Electrical Quantities

- In an atom, there is a central **nucleus**. The nucleus is made up of **protons** and **neutrons**. Around the nucleus are the orbiting **electrons**. There are positive and negative charges in the atom. Protons are the positive charges while electrons are the negative charges.
- Positive charges repel other positive charges. Negative charges repel other negative charges. Positive charges attract negative charges.
- **S** An **electric field** is a region in which an electric charge experiences a force.
- **S** The direction of an electric field at a point is the direction of the force on a positive charge at that point.
- Electric current is related to the flow of charge.
- **S** **Electric current** is the charge passing a point per unit time.

  $I = \dfrac{Q}{t}$ where I = current (in A)
  Q = charge (in C)
  t = time taken (in s)
- **S** **Conventional current** is from positive to negative and that the flow of free electrons is from negative to positive.
- An **ammeter** is used to measure the magnitude and direction of an electric current in an electric circuit.
- **Direct current (d.c.)** flows in a single direction only, whereas **alternating current (a.c.)** changes direction frequently.
- **Electromotive force (e.m.f.)** is the electrical work done by a source in moving a unit charge around a complete circuit.

  S $E = \dfrac{W}{Q}$ where E = e.m.f (in V)
  W = work done (in J)
  Q = charge (in C)
- **Potential difference (p.d.)** is the work done by a unit charge passing through a component.

S $V = \frac{W}{Q}$ where V = p.d. (in V)
W = work done (in J)
Q = charge (in C)

- A **voltmeter** is used to measure the e.m.f. of a dry cell or the p.d. across a component.
- The **resistance** R of a component is the potential difference V across it divided by the current I flowing through it.

S $R = \frac{V}{I}$ where R = resistance of the component (in Ω)
V = p.d. across the component (in V)
I = current flowing through the component (in A)

- **Ohm's Law** states that the current passing through a metallic conductor is directly proportional to the potential difference across it, provided that physical conditions (such as temperature) remain constant.
- The resistance R of a conductor depends on its temperature, length l and cross-sectional area A (or thickness).
- **Electrical power** P can be expressed as follows:
  $P = IV$ where P = power (in W)
  I = current (in A)
  V = potential difference (in V)
- **Electrical energy** E can be expressed as follows:
  $E = Pt = IVt$ where E = electrical energy (in J)
  P = power (in W)
  t = time (in s)
  I = current (in A)
  V = potential difference (in V)

Chapter 17: Electric Circuits and Electrical Safety

- We use circuit diagrams to represents electric circuits.
- **S** Diodes are components that allow current to flow through them in one direction only.
- In a **series circuit**, the components are connected one after another in a single loop. A series circuit has only one path through which electric charge can flow. The current at every point in a given series circuit is the same.
- **S** For n resistors placed in series, the p.d. V_E across the whole circuit (i.e. across all of the components) is equal to the sum of the p.d.s across each component.
  $V_E = V_1 + V_2 + \ldots + V_n$
- For n resistors in placed in series, the combined resistance is the sum of all the resistances.
  $R = R_1 + R_2 + \ldots + R_n$
- In a **parallel circuit**, the components are connected to the e.m.f. source in two or more loops. A parallel circuit has *more than one path through which electric charge can flow*.
- For n branches in parallel, the main current I is the sum of all the current in each branch.
  $I = I_1 + I_2 + \ldots + I_n$
- **S** The reciprocal of the combined resistance of resistors in parallel, $\frac{1}{R}$, is equal to the sum of the reciprocal of all the individual resistances.
  $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$
- A **potential divider** is a line of resistors connected in series. It is used to provide a fraction of the available p.d. from a source to another part of the circuit.
- The equation for two resistors used as a potential divider is as follows:
  $\frac{R_1}{R_2} = \frac{V_1}{V_2}$ where V_1 = p.d. across R_1 and V_2 = p.d. across R_2
- Potential dividers that are used to *vary* the output voltage from a source are called **variable potential dividers**.
- **Input transducers** are electronic devices that respond to changes in physical conditions, such as temperature and light. They can be used in potential dividers to vary the output voltage.
- A **thermistor** is a resistor whose resistance varies with temperature. An NTC thermistor has resistance that decreases as its temperature increases.
- A **light-dependent resistor (LDR)** has a resistance that decreases as the amount of light shining on it increases, and vice versa.
- **Trip switches** are safety devices that can switch off the electrical supply in a circuit when large currents flow through them.
- A **fuse** is a safety device added to an electrical circuit to prevent excessive current flow.
- **Switches** are designed to break or complete an electrical circuit.
- The **live wire** (brown) is connected to a high voltage and delivers current to the appliance. This is the wire to which trip switches, fuses and switches are fitted.
- The **neutral wire** (blue) completes the circuit by providing a return path to the supply for the current. It is usually at 0 V.
- The **earth wire** (green and yellow) is a low-resistance wire. It is usually connected to the metal casing of appliances.
- A fused plug connects an electrical appliance to the mains supply via the power socket. The fused plug commonly used in some countries is the **three-pin plug**.
- **Double insulation** is a safety feature that can replace the earth wire.

Chapter 18: Electromagnetic Effects

- **Electromagnetic induction** is the process through which an induced e.m.f. is produced in a conductor due to a *changing magnetic field*.
- **Faraday's Law** of electromagnetic induction states that the magnitude of the induced e.m.f. in a circuit is directly proportional to the rate of change of magnetic flux in the circuit.
- **S** **Lenz's Law** states that the direction of the induced e.m.f., and hence the induced current in a closed circuit, is always such that its magnetic effect opposes the motion or change producing it.
- **S** The **alternating current (a.c.) generator** uses alternating current to transform mechanical energy into electrical energy.
- In a simple a.c. generator, the direction of the induced current flowing in the coil can be found using **Fleming's right-hand rule**.
- In **a fixed coil a.c. generator**, the magnets rotate with respect to fixed coils.
- **Electromagnetism** is the relationship between electricity and magnetism.
- A current-carrying conductor produces a magnetic field around it. We can determine the direction of the magnetic field around the wire using the **right-hand grip rule**.
- **S** The strength of the magnetic field of a current-carrying wire increases when the current is increased.
- **S** We can deduce the direction of the force acting on a current-carrying conductor in a magnetic field using **Fleming's left-hand rule**.
- Conductors carrying currents in opposite directions repel.

- Conductors carrying currents in the same direction attract.
- The direction of the force on a beam of charged particles is reversed when we reverse the direction of the magnetic field.
- A current-carrying wire coil placed between two poles of a strong magnet experiences a **turning effect**.
- A **d.c. motor** is used to convert electrical energy to mechanical energy.
- A **transformer** is a device that can change a high alternating voltage (at low current) to a low alternating voltage (at high current), or vice versa. It has a **primary coil** and a **secondary coil** wound around a laminated soft iron core.
- Electrical energy is transferred from the primary coil to the secondary coil in a transformer. The voltages and the number of turns in the primary and secondary coils are related by this formula:

  $\frac{V_p}{V_s} = \frac{N_p}{N_s}$ where V_S = secondary (output) voltage (in V)
  V_P = primary (input) voltage (in V)
  N_S = number of turns in secondary coil
- In a **step-up** transformer, the number of turns in the secondary coil is greater than that in the primary coil. This results in an output voltage that is higher than the input voltage.
- In a **step-down** transformer, the number of turns in the secondary coil is less than that in the primary coil, so that the output voltage produced is lower than the input voltage.
- S In an ideal transformer, there is no power loss (i.e. the efficiency is 100%). The power supplied to the primary coil is fully transferred to the secondary coil.

  $I_pV_p = I_sV_s$ where V_s = secondary (output) voltage (in V)
  V_p = primary (input) voltage (in V)
  I_s = current in secondary coil (in A)
  I_p = current in primary coil (in A)
- The efficiency of a transformer can be calculated using the following equation:

  $$\text{Efficiency} = \frac{\text{output power}}{\text{input power}}\ 100\%$$

Chapter 19: Nuclear Model of the Atom

- An **atom** consists of a positively charged nucleus and negatively charged electrons in orbit around the nucleus.
- An atom which loses electrons has more positive charges – it becomes a **positive ion**.
- An atom which gains electrons has more negative charges – it becomes a **negative ion**.
- The scattering of alpha (α-) particles by a sheet of thin metal provide evidence to support the nuclear model of the atom.
- The **nucleus** of an atom consists of **protons** (positively charged) and **neutrons** (no charge).
- The **relative charge of an electron is –1** (because it is negative) and the **relative charge of a proton is +1**. As the neutron does not carry any charge, the **relative charge of a neutron is 0**.
- The number of protons in an atom is called the **proton number** or atomic number, represented by *Z*.
- The total number of neutrons and protons in a nucleus is called the **nucleon number**, represented by *A*.
- **The number of neutrons in a nucleus = nucleon number *A* – proton number *Z***.
- **Isotopes** of an element are the atoms that have the same number of protons but different number of neutrons in the nucleus.
- S **Nuclear fission** is a process in which the nucleus of an atom splits (usually into two parts) and releases a huge amount of energy.
- S The **relative charge on the nucleus** is the same as the proton number *Z* of the nucleus.
- S **Nuclear fusion** is a process in which two light atomic nuclei combine to form one heavier atomic nucleus, releasing a huge amount of energy.
- S The total number of nucleons before and after the a nuclear fission or fusion reaction is the same. The total relative charge before and after should also be the same.

Chapter 20: Radioactivity

- **Ionising radiation** is radiation with high energies that can *knock off electrons from atoms to form ions*.
- **Background radiation** is ionising nuclear radiation in the environment when no radioactive source is deliberately introduced.
- The background count rate is measured in **counts per minute (counts/min)**.
- When carrying out any measurements with radioactive sources, you should first measure the background radiation. Subtract this background count rate from your measurements to obtain the corrected count rate for the radioactive source.
- The radiation emitted by a radioactive nucleus is **spontaneous and random** in direction.
- An **α-particle** consists of two protons and two neutrons tightly bound together without any orbiting electrons. It is Identical to a helium nucleus.
- A **β-particle** is a fast-moving electron ejected from a radioactive nucleus.
- A **γ-ray** is an electromagnetic radiation emitted by a nucleus with excess energy.
- A change in an unstable nucleus can result in the emission of α-particles or β-particles and/or γ-radiation. This nuclear process is called **radioactive decay**.
- When a nucleus undergoes **α-decay**, it emits an α-particle. When a nucleus undergoes **β-decay**, it emits a β-particle.
- During α- or β-decay, the nucleus changes to that of a different element.
- The **half-life** of a radioactive isotope is the time taken for half the nuclei of that isotope in any sample to decay.
- The graph of count rate against time is called the **decay curve**.
- Applications of radioactivity include household fire alarm, sterilisation of food and equipment, measuring and controlling thickness of materials
- S Ionising nuclear radiation damages living cells. The energy carried by the radiation *can kill cells and cause mutation and cancer*.
- S Exposure to ionising radiation can be controlled by *reducing exposure time, increasing distance between source and living tissue* and *shielding*.

Chapter 21: Earth and the Solar System

- The Earth is a **planet**. Planets orbit a star. Our star is the Sun.
- The Earth takes about 365 days or one **year** to orbit the Sun.
- The Earth also rotates on its axis and it takes about 24 hours or one **day** *to rotate once*. The Earth's *axis is tilted* at an angle of about 23.5 degrees towards the plane of its orbit.
- The day and night cycle is due to the Earth's rotation about its tilted axis.
- On the Earth, we see the Sun move across the sky from East to West. This apparent movement is because the Earth is spinning about its axis as it orbits the Sun.

- Temperate countries have different weather patterns at different times of the year. These weather patterns are called the **seasons**.
- Seasons occur because the Earth orbits the Sun on a tilt.
- The Earth has one *natural satellite* called the **Moon**.
- The different appearances of the Moon in the sky are known as the **phases of the Moon**.
- Ⓢ The Moon's **average orbital speed** around the Earth:

$$\boldsymbol{v = \frac{2\pi r}{Q}}$$ where v = average orbital speed (in m/s)
r = average orbital radius
T = orbital period

- The Solar System was formed from a swirling cloud of gas and dust in space called **nebula.**
- A hot spinning mass called a **protostar** was formed at the centre of a swirling disc of gas and dust. The swirling disc is called an **accretion disc**.
- **Accretion** is the accumulation of particles into a massive object by gravitational attraction.
- Ⓢ Objects in the Solar System move in an **elliptical orbit**.
- Ⓢ As the distance of planets from the Sun increases, the orbital speed decreases due to decreasing gravitational field of the Sun. This means the time to orbit the Sun also increases.

Chapter 22: Stars and the Universe

- The Sun is an average yellow star consisting of mostly hydrogen and helium.
- The Sun radiates the energy in the form of electromagnetic radiation — mostly infrared, visible light and ultraviolet.
- Ⓢ Stars are powered by nuclear reactions that release energy.
- Ⓢ In stable stars, the nuclear reactions involve the fusion of hydrogen into helium.
- The **Milky Way** is a group of many billions of stars or a galaxy to which our Sun belongs.
- Ⓢ One **light-year** is equal to 9.5×10^{15} m.
- **Redshift** is the increase in the observed wavelength of electromagnetic radiation emitted from stars and galaxies which are moving away from the Earth.
- At some moment in the past, all of the matter in the Universe must have exploded outwards from this point and it is still expanding. This is known as the **Big Bang Theory** of the Universe.
- Ⓢ If the Big Bang Theory is correct, the Universe should now be filled with microwaves. These microwaves are called the **cosmic microwave background radiation** or **CMBR**.
- Ⓢ The **Hubble constant H_0** is defined as the ratio of the speed at which the galaxy is moving away from the Earth to its distance from the Earth.

$$\boldsymbol{H_0 = \frac{v}{d}}$$ where H_0 = Hubble constant
v = speed of movement away from the Earth
d = distance from the Earth

- Ⓢ The current estimate of H_0 is **2.2×10^{-18} per second**.

Answers

This section only includes short and numerical answers.

Chapter 1: Measurement of Physical Quantities

Quick Check
p. 4: True p. 9: False p. 12: True

Let's Practise 1.1
1 1.0×10^{-5} m **2** 2.53 cm **3** **(a)** m^3 **5** 4 s

Let's Practise 1.2
2 25 N, at 36.9 (anticlockwise) from the 20 N

Let's Review
Section A: Multiple-choice Questions
1 B **2** B **3** D **4** D **5** A

Section B: Short-answer and Structured Questions
1 **(a)** Length; Five; Metres **(b)** Time; Two; Seconds
(c) Mass; One thousand; Kilograms
2 **(a)** 2.05 cm
(b) Vernier calipers: 0.01 cm; Metre rule: 0.1 cm
4 $g = 9.9$ m/s^2
5 4243 N

Chapter 2: Motion

Quick Check
p.19: False p.21: False p.22: True p. 24: True; True
p. 26: True p. 31: True

Let's Practise 2.1
1 8 m/s **2** 0.6 m/s^2

Let's Practise 2.2
1 **(a)** $s = 0$ m; $v = 0$ m/s **(b)** $s = 160$ m; $v = 10$ m/s
(c) $s = 280$ m; $v = 0$ m/s

Let's Practise 2.3
1 **(b)** 50 m/s **(c)** 125 m

Let's Review
Section A: Multiple-choice Questions
1 B **2** D **3** A **4** D

Section B: Short-answer and Structured Questions
1 40 km/h
2 **(a)** 3 m/s^2 **(b)** Acceleration is zero **(c)** 2 m/s^2
(d) Acceleration is zero **(e)** Non-uniform deceleration
3 **(a)** The train is decelerating from $t = 12$ s to $t = 16$ s.
(b) 20 m/s^2
(c) **(i)** 520 m **(ii)** 32.5 m/s

Chapter 3: Mass, Weight and Density

Quick Check
p. 39: True p. 42: False

Let's Practise 3.1
3 100 N **4** 2.75×10^3 N

Let's Practise 3.2
1 density $= \dfrac{\text{mass}}{\text{volume}}$; SI unit: kg/m^3
2 1 cm^3 of water has a mass of 1.0 g
4 0.92 g/cm^3

Let's Review
Section A: Multiple-choice Questions
1 C **2** D **3** C

Section B: Short-answer and Structured Questions
2 **(a)** No change **(b)** No change
(c) Decrease **(d)** Increase
3 **(a)** No **(b)** **(i)** 0.518 cm^3 **(ii)** The piece of gold will sink.
4 **(a)** 14 900 g **(b)** 3000 cm^3 **(c)** 2 cm^2
5 **(a)** No

Chapter 4: Forces

Quick Check
p. 52: False p. 57: False p. 61: True p. 65z; True

Let's Practise 4.1
1 **(a)** 4.0 cm **(c)** N/cm **(d)** 7.0 cm

Let's Practise 4.2
1 **(a)** False **(b)** False **(c)** False **(d)** True **(e)** True
(f) True **(g)** False **(h)** False **(i)** False **(j)** True

Let's Practise 4.3
1 Moment = force × perpendicular distance from the pivot
2 no resultant force; no resultant moment
3 **(a)** 30 cm **(b)** 300 N m **(c)** 87.5 cm
4 320 N

Let's Practise 4.4
1 The centre of gravity of an object is the point through which the weight of the object acts.
2 Yes

Let's Review
Section A: Multiple-choice Questions
1 B **2** D **3** C **4** A **5** D **6** C **7** C

Section B: Short-answer and Structured Questions
1 **(a)** 5 N **(b)** 50 N
2 **(a)** N m
(b) **(i)** No resultant force and no resultant moment.
(ii) 2.5 m
3 **(a)** 30 000 N m **(b)** 7500 N **(c)** 2.4 m
4 200 N

Chapter 5: Momentum

Quick Check
p. 73: True p. 77: True p. 80: False

Let's Practise 5.1
1 mass × velocity **2** kg m/s
3 Vector **4** 4.8 kg m/s

Let's Practise 5.2
1 force × time **2** N s or kg m/s **3** Vector
4 momentum; time **5** 6 N s

Let's Practise 5.3
2 3.8 m/s

Let's Review
Section A: Multiple-choice Questions
1 A **2** C **3** D **4** D **5**

Section B: Short-answer and Structured Questions
1 **(a)** mass × velocity **(b)** **(i)** 16 000 kg m/s **(ii)** 1.6 m/s
2 **(a)** 80 kg m/s **(b)** 80 N s **(c)** 40 m/s
3 **(a)** 40 kg m/s **(b)**–40 kg m/s **(c)** –0.8 m/s

Chapter 6: Energy, Work and Power

Quick Check
p. 88: True p. 92: True p. 96: True

Let's Practise 6.1
1 **(a)** Electrical energy → Thermal energy
(b) Chemical potential energy
→ Electrical energy → Light and heat energy
3 Kinetic energy
→ Gravitational potential energy → Kinetic energy
4 **(a)** 900 J **(b)** 30 m/s

Let's Practise 6.2
3 **(a)** 24 J **(b)** 24 J **4** **(a)** 500 J **(b)** 500 J

Let's Practise 6.3
1 Combustion of fuel **2** **(a)** Nuclear fission
3 Only 45% of the input energy is converted into useful output.
4 70%

Let's Practise 6.4
2 100 W **3** 1.8 MJ
4 The 1000 W kettle will take half the time it takes for the 500 W kettle to bring the water to a boil.

Let's Review
Section A: Multiple-choice Questions
1 B **2** B **3** C **4** A **5** B

Section B: Short-answer and Structured Questions
1 **(b)** Gravitational potential energy **(c)** Kinetic energy
2 **(b)** **(i)** Nuclear energy; Fossil fuels; Biofuels
3 **(a)** 2×10^{-3} J **(b)** 1.5×10^{-3} J
4 **(b)** **(i)** 9 J **(ii)** 12 J **(iii)** 75%
5 **(a)** **(i)** 300 kJ **(b)** **(i)** 240 kJ **(ii)** 17.9 m s^{-1}
6 **(a)** **(i)** P = 30.4%; Q = 12.5%; R = 40.4%; S = 35.7%; T = 20.5%
(b) 868.1 MJ

Chapter 7: Pressure
Quick Check
p. 105: True p. 107: False p. 109: True

Let's Practise 7.1
1 Pressure $= \frac{\text{force}}{\text{area}}$
3 **(a)** 50 N **(b)** 0.562 m^2 **(c)** 0.75 m **4** Upright

Let's Practise 7.2
1 Density of the liquid; Depth of the liquid in which the object is being immersed in
2 **(a)** greater **(b)** smaller **3** $\Delta p = \rho g \Delta h$
4 51 250 Pa

Let's Review
Section A: Multiple-choice Questions
1 C **2** D **3** C

Section B: Short-answer and Structured Questions
2 **(a)** The pressure on the ball bearing increases.
(b) The change in pressure is greater.
3 **(a)** 2500 Pa or N/m^2 **(b)** 968 Pa or N/m^2

Chapter 8: Kinetic Particle Model of Matter
Quick Check
p. 113: True p. 118: False p. 121: True

Let's Practise 8.1
1 **(a)** A gold ring has a fixed shape.
(b) Milk has no fixed shape.
(c) Air can be compressed.

Let's Practise 8.3
2 **(b)** $pV = k$ or pV = constant

Let's Review
Section A: Multiple-choice Questions
1 A **2** D **3** B **4** D **5** B

Section B: Short-answer and Structured Questions
1 **(a)** Smoke particles
3 **(a)** The pressure will be doubled to 2×10^5 Pa
(b) 1.2×10^5 Pa **(c)** 170 cm^3

Chapter 9: Thermal Properties and Temperature
Quick Check
p.128: False p.131: False p.139: True

Let's Practise 9.1
1 Expansion can cause metal railway lines to buckle.
2 Thermal energy causes them to expand and become longer.

Let's Practise 9.2
1 **(a)** Increase **(b)** Increase **(c)** Decrease **(d)** Increase
3 1111 J/(kg K)

Let's Practise 9.3
4 Any two of the following: Windy day; Sunny day; Hot day
5 Difference: Boiling occurs throughout the liquid, evaporation takes place at the surface; Similarity: Both evaporation and boiling involve a liquid changing into a gas. (Accept other possible answers.)

Let's Review
Section A: Multiple-choice Questions
1 A **2** D **3** C **4** C **5** A

Section B: Short-answer and Structured Questions
1 **(b)** Liquid-in-glass thermometer
2 **(a)** **(ii)** Solidifying/Freezing **(b)** 60°C
3 **(a)** 50 J **(b)** 12.5°C **4** 400 J/(kg K)

Chapter 10: Transfer of Thermal Energy
Quick Check
p. 146: True p. 147: False p. 148: True p. 151: True

Let's Practise 10.1 and 10.2
1 Through conduction, convection and/or radiation

Let's Practise 10.3
1 **(a)** The density of the material decreases.

Let's Practise 10.4
1 Infrared radiation
2 Dark colours are good absorbers of infrared radiation.
4 Any three of the following: Colour of the surface; Texture of the surface; Surface area; Surface temperature

Let's Practise 10.5
1 **(a)** **(i)** Conduction **(ii)** Convection

Let's Review
Section A: Multiple-choice Questions
1 D **2** C **3** B

Section B: Short-answer and Structured Questions
1 **(c)** The hot tea will emit infrared radiation to its surroundings.
3 **(d)** Cork is a bad thermal conductor. It is used to reduce thermal energy transfer by conduction.

Chapter 11: General Properties of Waves
Quick Check
p.164: False p.167: False p.170: False; True p.174: False

Let's Practise 11.1
1 **(a)** Incorrect **(b)** Correct **(c)** Correct

2 (b) Transverse waves: sea waves; Longitudinal waves: sound waves

Let's Practise 11.2
1 (a) 0.1 s **(b)** 10 Hz **(c)** 0.1 cm
2 $v = f\lambda$ **3** $T = 2.0$ s

Let's Practise 11.3
1 (a) The water waves have diffracted through the gaps.

Let's Review
Section A: Multiple-choice Questions
1 B **2** D **3** D **4** C **5** C **6** C **7** D

Section B: Short-answer and Structured Questions
1 (a) It means two complete waves per second.
(b) (ii) $f = 10$ Hz
2 (a) 2 Hz **(b)** $\lambda = 1.5$ m
5 (a) 0.6 m **(b)** 5 m **(c) (i)** 1.25 s **(ii)** 0.8 Hz **(iii)** 4 m/s

Chapter 12: Light
Quick Check
p. 188: True p. 195: False p. 205: True

Let's Practise 12.1
2 Upright; Laterally inverted; Same size as the object; Virtual; Same distance from the mirror as the object
3 (b) The image is upright, laterally inverted, virtual, the same size as the object, and the same distance from the mirror as the object.
4 6.5 m

Let's Practise 12.2
2 Refractive index $n = \dfrac{\sin i}{\sin r} = \dfrac{c}{v}$

Let's Practise 12.3
3 $c = 31.8°$ **4** Glass prisms and optical fibres

Let's Practise 12.6
1 Violet, indigo, blue, green, yellow, orange, and red.
2 Red

Let's Review
Section A: Multiple-choice Questions
1 B **2** B **3** D **4** C **5** D **6** D **7** D **8** B **9** C
10 D **11** B **12** B **13** B **14** B **15** C

Section B: Short-answer and Structured Questions
1 (a) (ii) Upright; Laterally inverted; Same size as the object; Virtual; Same distance from the mirror as the object
(b) 30 m **2 (b) (i)** $n = 1.46$ **(ii)** $x = 20°$; $y = 30°$
3 (a) (i) Diamond **(ii)** Air **(b)** $v = 1.76 \times 10^8$ m/s **(c)** 1.5
4 (a) Angle of refraction in air = 62.9° **(b)** $c = 48.8°$
5 (a) $r = 28.1°$ **7 (a) (i)** 75 cm **(ii)** 70 cm **(b)** 2 m/s
8 (b) 220 cm **9 (b)** Angle of refraction at Q is 28°.

Chapter 13: Electromagnetic Spectrum
Quick Check
p. 218: False; True

Let's Practise 13.1
1 (a) Gamma rays **(b)** Radio waves
2 (a) Radio waves **(b)** Gamma rays

Let's Practise 13.2
1 (b) Visible light; Radio waves
2 Microwaves
3 (a) Direct satellite television and satellite phones
(b) Satellite phones

Let's Practise 13.3
1 (a) 3×10^8 m/s **(b)** 3×10^8 m/s **(c)** 3×10^8 m/s
(d) 3×10^8 m/s
2 Can pass through some walls, only a short aerial is needed
3 Visible light; Infrared

Let's Review
Section A: Multiple-choice Questions
1 C **2** C **3** B **4** D **5** A **6** D

Section B: Short-answer and Structured Questions
1 (a) A: Infrared; B: Ultraviolet; C: Gamma rays; D: Frequency
2 (a) 3.75×10^8 m **(b)** 30 m
3 (a) A

Chapter 14: Sound
Quick Check
p. 225: False p. 227: False p. 232: True
Let's Practise 14.1
2 Yes

Let's Practise 14.2
1 No **2** 333 m/s

Let's Practise 14.3
1 750 m
2 Ultrasound is less hazardous than X-rays due to its lower energy.

Let's Practise 14.4
1 (a) Amplitude **(b)** Frequency

Let's Review
Section A: Multiple-choice Questions
1 C **2** C **3** B **4** D

Section B: Short-answer and Structured Questions
3 (a) 329 m/s
4 (a) Dogs can detect sound of frequencies above 20 000 Hz.
5 (b) Depth of seabed = 225 m
6 (b) He will not succeed.

Chapter 15: Simple Phenomena of Magnetism
Quick Check
p. 240: True p. 241: False p. 246: False

Let's Practise 15.1
1 (a) Any three of the following: Iron; Steel; Cobalt; Nickel
(b) Any three of the following: Copper; Wood; Plastic; Brass
3 (a) Wood does not completely block the magnetic field.

Let's Practise 15.2
1 Metal 1: Iron Metal 2: Steel Metal 3: Brass

Let's Review
Section A: Multiple-choice Questions
1 C **2** D **3** C

Section B: Short-answer and Structured Questions
1 (c) Iron

Chapter 16: Electrical Quantities
Quick Check
p. 258: False p. 261: False p. 263: True p. 265: False
p. 267: True

Let's Practise 16.1
1 Positive charges and negative charges

2 **(a)** The two rods attract each other.

Let's Practise 16.2
1 The two directions are the same.

Let's Practise 16.3
1 $I = \frac{Q}{t}$ **2** Ampere **3** 6.25×10^{18} electrons

Let's Practise 16.4
2 **(a)** 48 C **(b)** 144 J

Let's Practise 16.5
1 As the temperature increases, the resistance increases.

Let's Practise 16.6
1 2.16 kW **2** \$26.24

Let's Review
Section A: Multiple-choice Questions
1 B **2** B **3** C **4** B **5** D **6** B **7** D

Section B: Short-answer and Structured Questions
1 **(b)** 16.2 kWh
2 **(a)** Wire A = 10 W; Wire B = 4 W **(b)** Wire A is longer than wire B.
(c) Wire A = 0.5 A; Wire B = 1.25 A
3 **(b)** **(i)** 2×10^{-3} A
4 **(b)** **(i)** 32 **(ii)** 0.53 A **(iii)** 22.5 Ω
6 **(a)** Conductor A = 15.0 Ω; Conductor B = 3.3 Ω
(b) **(i)** Conductor B

Chapter 17: Electrical Circuits and Electrical Safety

Quick Check
p. 277: True p. 278: False p. 280: False p. 287: False
p. 291: False

Let's Practise 17.2 and 17.3
1 **(a)** 25 Ω **(b)** I_1= 0.1 A; I_2= 0.3 A **(c)** 17 Ω **(d)** 75 Ω

Let's Practise 17.4
1 1 V at 0°C; 4 V at 100°C

Let's Review
Section A: Multiple-choice Questions
1 C **2** D **3** C **4** D **5** D **6** B **7** B
8 A **9** A **10** B **11** A

Section B: Short-answer and Structured Questions
1 **(a)** 1.3 Ω **(b)** 2 Ω **(c)** 3.3 Ω **(d)** 1.2 A
2 **(a)** 0.2 A **(b)** 0.6 A **(c)** 4 Ω
4 **(a)** There is no resistance between B and C.
(b) **(i)** 200 Ω **(ii)** 80 Ω
(c) The fault lies between C and D.
(d) **(i)** 500 Ω **(ii)** 75 Ω **(iii)** 50 Ω
(e) 100 Ω

Chapter 18: Electromagnetic Effects

Quick Check
p. 306: True p. 312: False p. 317: False
p. 321: False p. 323: True

Let's Practise 18.1
1 **(a)** The galvanometer needle is deflected to the left.
(c) An S pole is induced at end A.

Let's Practise 18.2
1 Slip rings; carbon brushes

Let's Practise 18.3
2 **(b)** Increase the number of turns per unit length of the solenoid; increase the magnitude of the current; place a soft iron core in the solenoid to concentrate the magnetic field lines

Let's Practise 18.4
1 **(a)** The force is downwards.
2 **(b)** The current could be increased and/or the wires could be placed closer to each other.

Let's Practise 18.5
1 Reverse the direction of the magnetic field; Reverse the direction of the current
3 Electrical energy to kinetic energy

Let's Practise 18.6
1 **(a)** **(i)** Soft iron **(ii)** Smaller **(b)** 0.04 A
2 Use thick wires to reduce the resistance of the cables; Transmit electricity at high voltage

Let's Review
Section A: Multiple-choice Questions
1 B **2** A **3** D **4** C **5** C **6** A **7** B **8** B **9** D

Section B: Short-answer and Structured Questions
1 **(b)** The magnitude of the current passing through a conductor
(c) The direction of the current passing through a conductor
2 **(b)** The number of turns in the solenoid; The strength of the magnet; The speed at which the magnet moves with respect to the solenoid
3 **(a)** The galvanometer is deflected in one direction.
(b) The galvanometer is deflected in the opposite direction.
(c) Same as **(a)** but the deflection of the galvanometer is larger.
7 **(a)** **(i)** 6.25 V **(ii)** 80 A **8** **(a)** 400 turns **(b)** 0.125 A
9 **(a)** step-up transformer
(b) **(i)** 500 A **(ii)** 800 000 A **(iii)** 1.73×10^{13} J
10 **(d)** The coil will rotate in the anticlockwise direction.

Chapter 19: Nuclear Model of the Atom

Quick Check
p. 333: True p. 335: True p. 339 True

Let's Practise 19.1
1 **(a)** positively; negatively **(b)** loses **(c)** gains electrons

Let's Practise 19.2
1 **(a)** +1 **(b)** 0 **(c)** –1
2 **(a)** The proton number is the number of protons in the nucleus. The nucleon number is the total number of protons and neutrons in the nucleus.
(b) ${}^{35}_{17}X$ **(c)** 18
(d) X and Y are isotopes of the same element

Let's Review
Section A: Multiple-choice Questions
1 C **2** D **3** B **4** D **5** B **6** A

Section B: Short-answer and Structured Questions
3 **(a)** Nuclear fission is a process in which the nucleus of an atom splits and releases huge amount of energy.

Chapter 20: Radioactivity

Quick Check
p. 345: False p. 351: True

Let's Practise 20.1

2 Any two of the following: Radon gas in the air; Rocks containing radioactive minerals; Food and drink; Cosmic rays from the Sun
3 21 counts/minute
4 4 counts/minute

Let's Practise 20.2

1 Emission of radiation from a nucleus is a random process.
The count rate will always vary.
3 **(a)** γ rays **4** Positively charged and high kinetic energy.

Let's Practise 20.3

1 **(a)** Radioactive decay; spontaneous; random (in either order for the last two blanks)
(b) element
2 Big nucleon number or massive nucleus; More neutrons compared to protons
3 **(a)** decreases by 4; decreases by 2
(b) remains the same; increases by 1; fewer
4 **(a)** ${}^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}\alpha + \gamma$ **(b)** ${}^{137}_{55}Cs \rightarrow {}^{137}_{56}Ba + {}^{0}_{-1}\beta + \gamma$

Let's Practise 20.4

1 **(b)** 15 h **(c)** 1100 counts/min **2** 115 counts/min

Let's Practise 20.5

1 Any two of the following: Kill cells; Cause mutation; Cancer.
2 Lead box **3** Time; Distance; Shielding

Let's Review

Section A: Multiple-choice Questions

1 D **2** D **3** D **4** B **5** D
6 C **7** C **8** C **9** A **10** A

Section B: Short-answer and Structured Questions

1 **(a)** 22 counts/min **(c)** Background radiation
4 **(a)** ${}^{60}_{27}Co \rightarrow {}^{60}_{28}Ni + {}^{0}_{-1}\beta + \gamma$ **(b)** 21.2 years
5 **(c)** α-particles are absorbed by the foil.

Chapter 21: Earth and the Solar System

Quick Check

p. 365: True p. 366: True p. 367: False p. 373: False

Let's Practise 21.1

1 planet; star; natural satellite
2 365 (or 365.25). **3** B
4 **(a)** True **(b)** False **(c)** False **(d)** True **5** 7800 m/s

Let's Practise 21.2

1 **(a)** Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune
3 **(a)** A natural satellite which orbits a planet.
(b) An irregularly shaped lump of rock left over from the formation of the Solar System.
4 500 s or 8 min and 20 s
5 **(b)** Any one of the following: Venus; Saturn; Uranus
(c) Jupiter **(d)** Mercury
(e) Any number between 2 and 12 years

Let's Review

Section A: Multiple-choice Questions

1 B **2** C

Section B: Short-answer and Structured Questions

2 towards**;** southern; Antarctic; winter
5 **(b)** An ellipse **(c)** A **(d)** C **(e)** D
6 **(b)** 3.1×10^3 m/s

Chapter 22: Stars and the Universe

Quick Check

p. 378: False p. 380: True p. 380: True

Let's Practise 22.1

1 **(a)** True **(b)** False **(c)** False **(d)** True

Let's Practise 22.2

1 **(a)** One thousand million
(b) The galaxy that contains our Solar System
2 **(a)** A red giant **(b)** A planetary nebula
(c) A supernova
(d) A white dwarf
4 9.5×10^{15} m

Let's Practise 22.3

2 C

Let's Review

Section A: Multiple-choice Questions

1 B **2** D

Section B: Short-answer and Structured Questions

2 **(b)** The graph would have a straight line through the origin.
(c) Age of Universe $= \dfrac{1}{\text{gradient}}$
3 **(a)** The left hand side of the galaxy is moving towards the Earth and the right hand side of the galaxy is moving away.
(b) The galaxy could be rotating.

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